SiPM
Photon Detector Developments for Experiments in High-Energy Physics, Astroparticle Physics, ...

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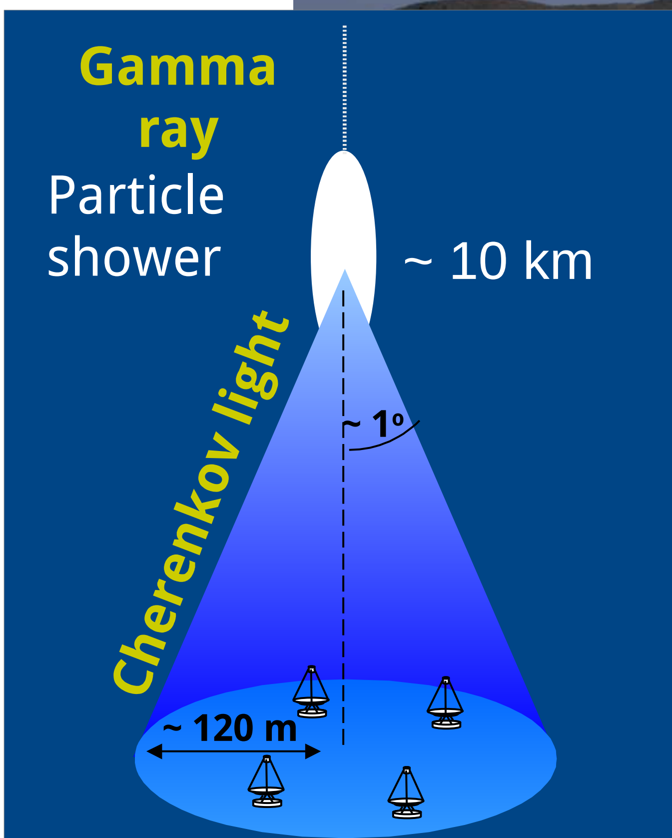
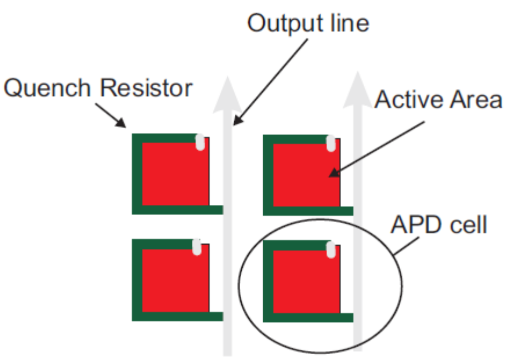
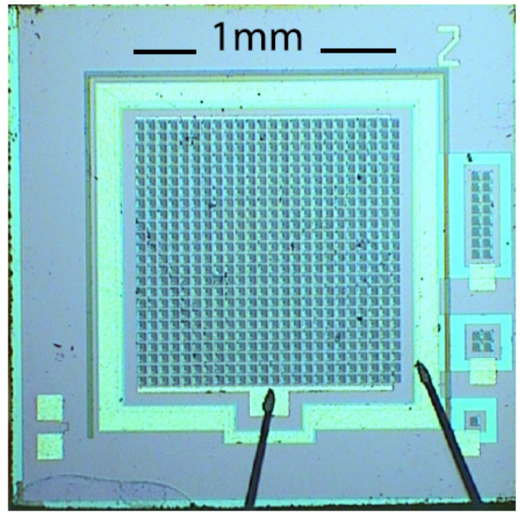


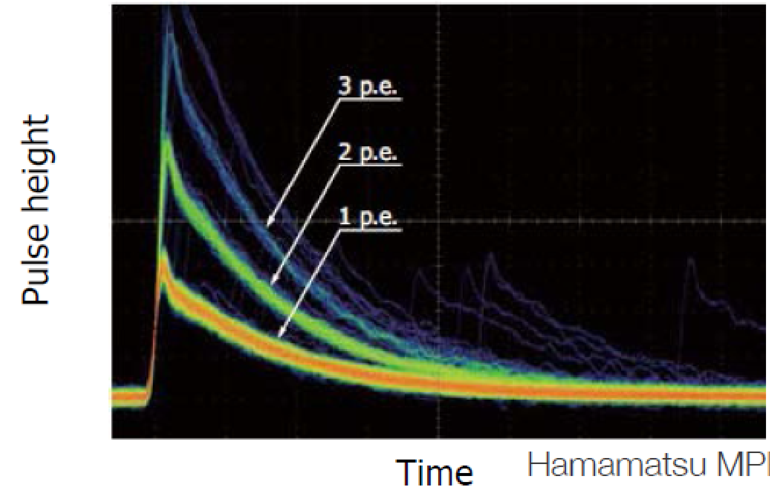
Gamma ray
Particle shower
~ 10 km
Cherenkov light
~ 1°
~ 120 m

The SiPM





MEPhI/Pulsar SiPM 2004



Hamamatsu MPPC techinfo

The SiPM concept provides multi-photon resolution:

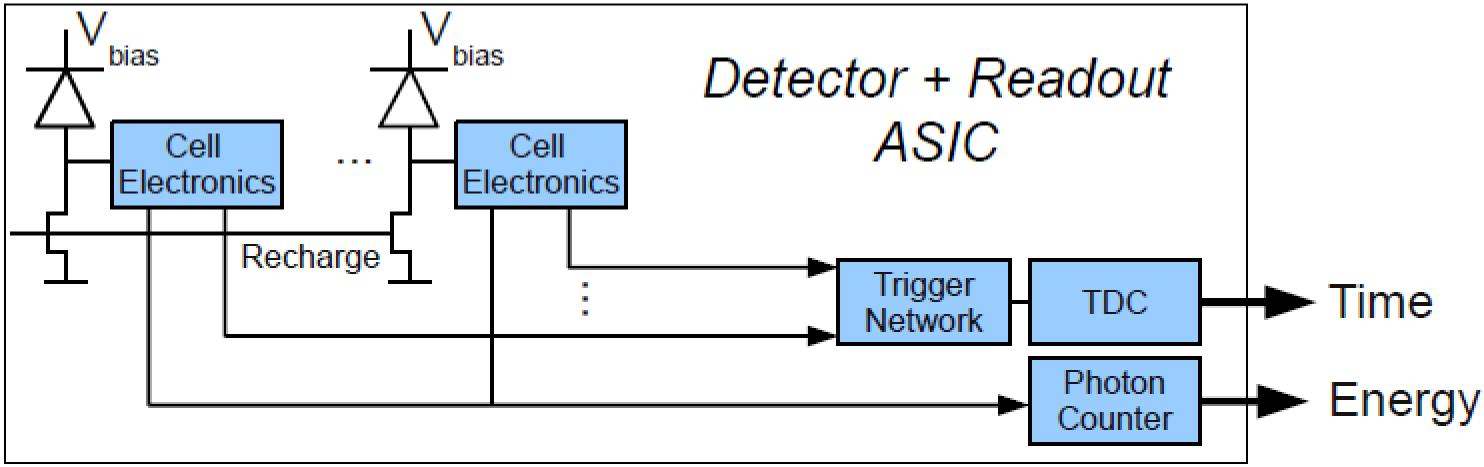
Many passively quenched SPADs are connected in parallel

Recover information about number of photons
if photons per cell per recovery time <1

Pioneered in the 90's
Key persons: Dolgoshein, Golovin, and Sadykov

For an extensive review on the history of solid state photon detectors see
D. Renker and E. Lorentz (2009)

SiPM with Active Quenching: dSiPM

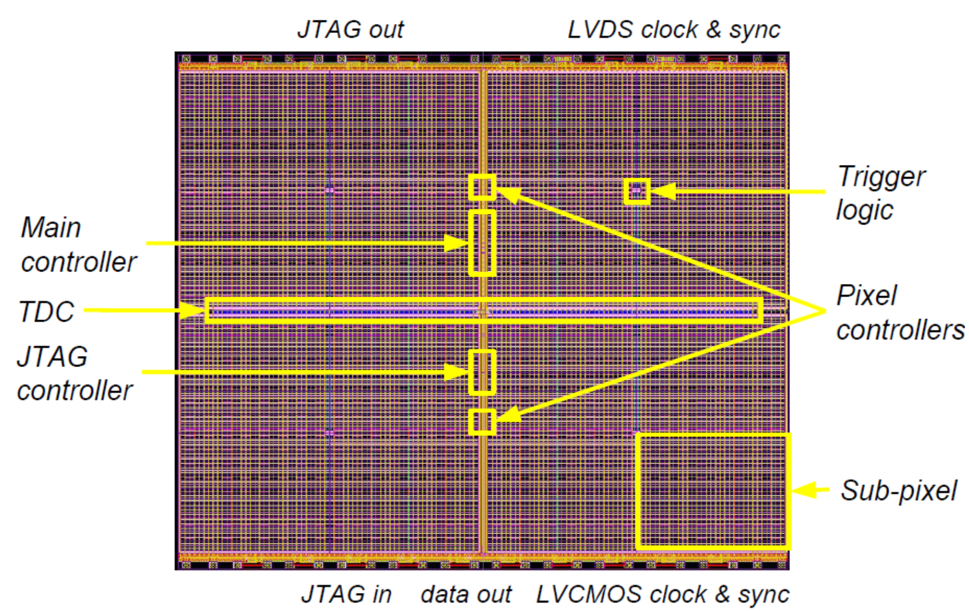


First commercial dSiPM from Philips

Individual pixels can be turned on/off

Excellent timing

Reduced geometrical efficiency → lower PDE (for now...)



SiPM Advantages and *Nuisances*

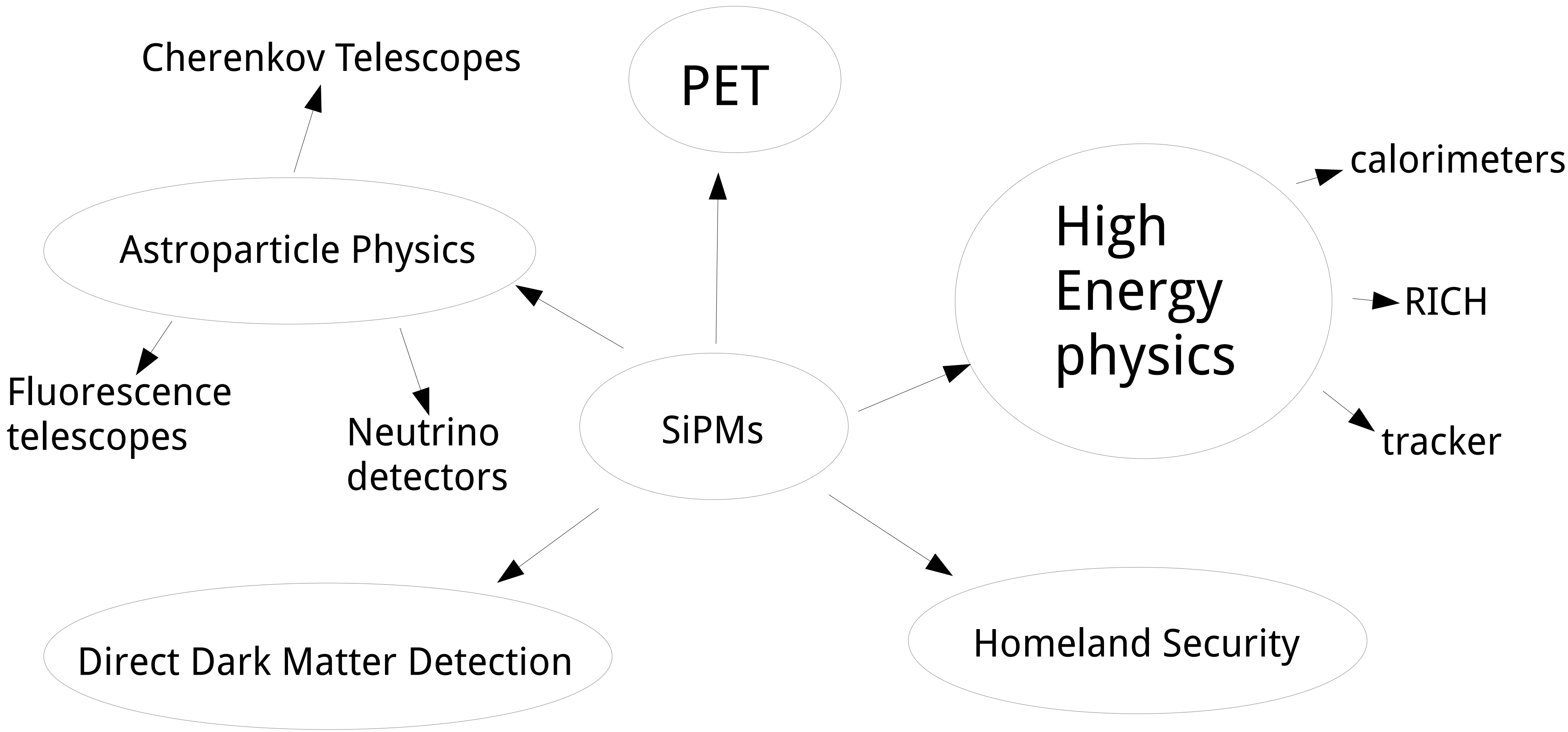
- Mechanical robust
- Compact
- Operating voltages < 100V
- Not damaged in bright light
- No aging
- Insensitive to magnetic fields
- Excellent SNR
- Excellent single photon timing (<100 ps)
- Very high photon detection efficiency

What's being worked on

- Radiation hardness
- Better UV sensitivity
- Lower optical crosstalk
- Lower dark rates
- Size

A near perfect device for many applications

SiPM Applications



Discussion shifts away from device features to how SiPMs can be best implemented

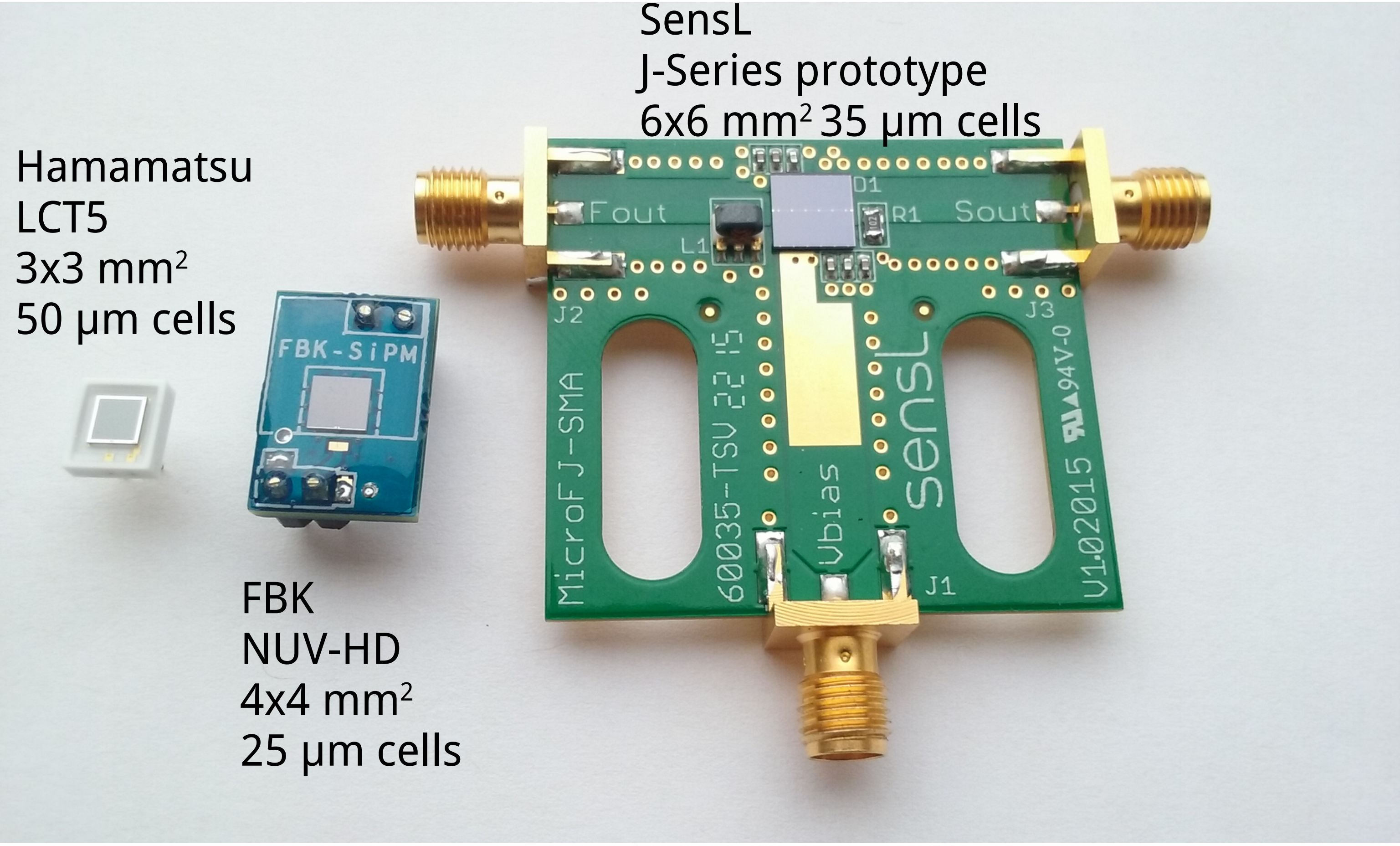
You have Choices

Number of producers increases

from W. Ootani

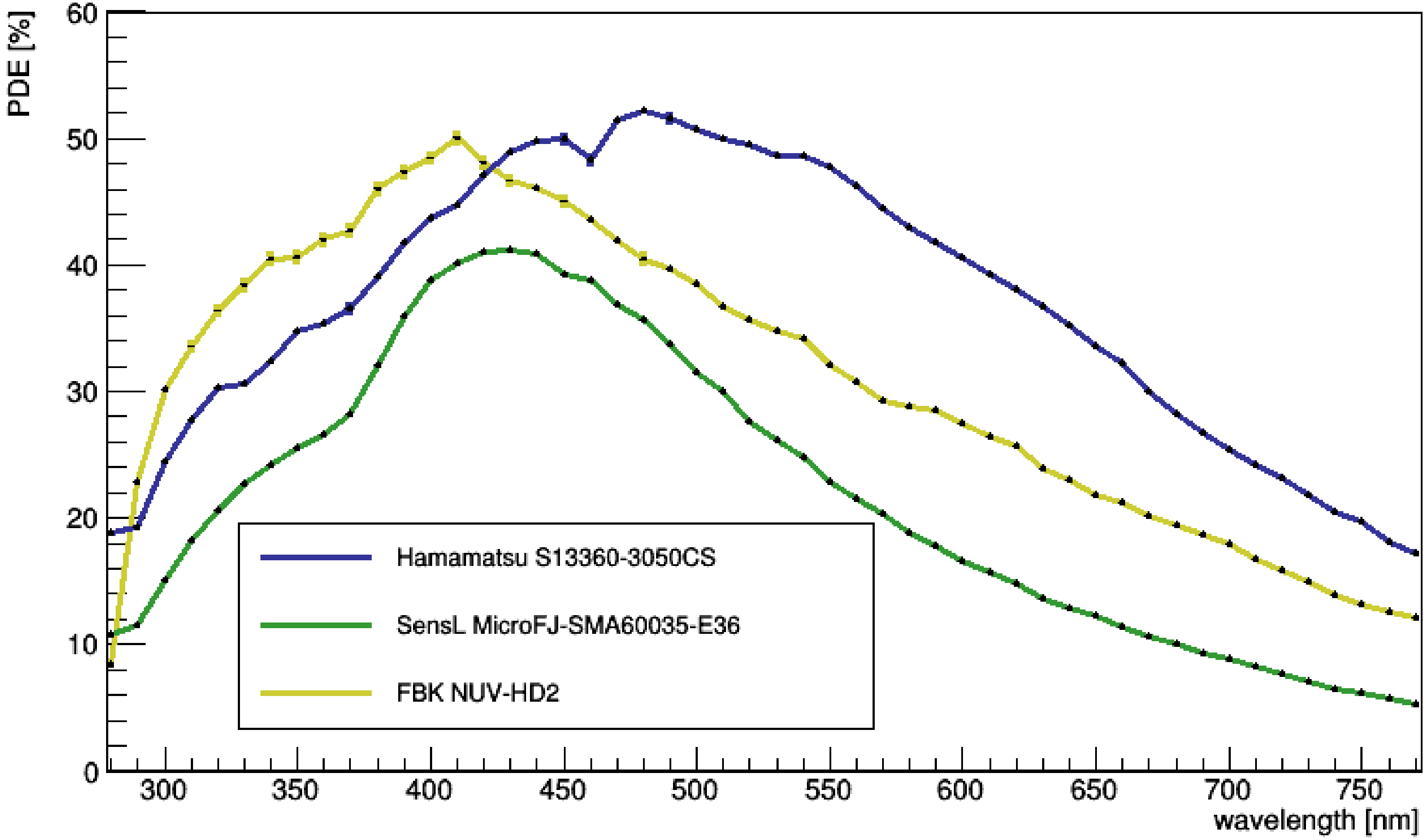
Interactions between producers and users are very productive!

Three recent Devices



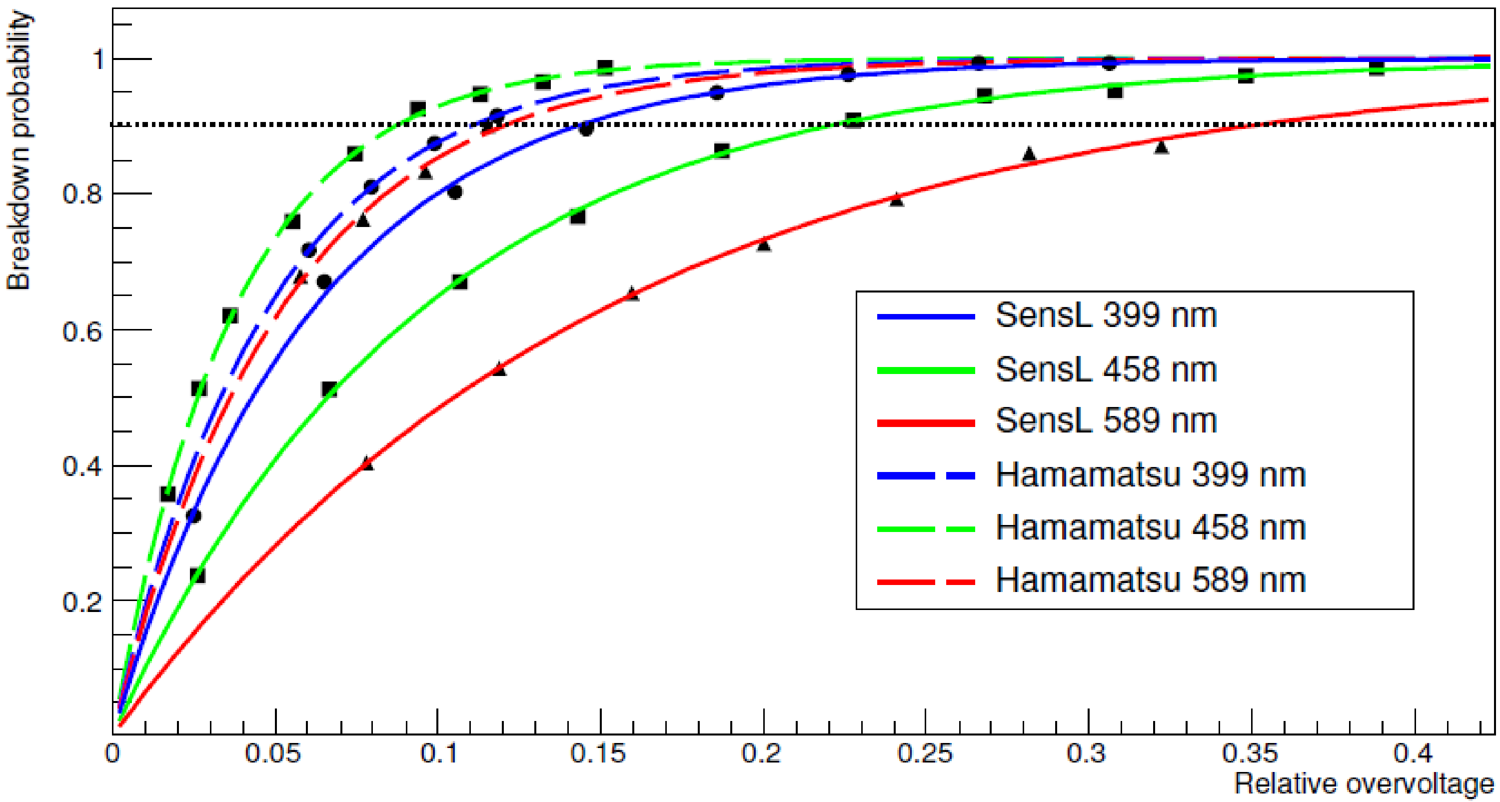
The selected three devices happen to be the last ones I tested.

Photon Detection Efficiency



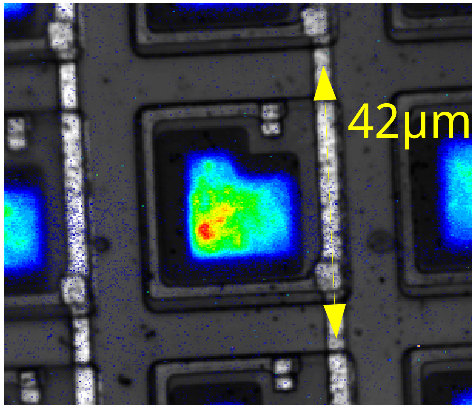
PDE = geometrical efficiency * (1-reflection losses) * QE * breakdown probability

Breakdown Probability

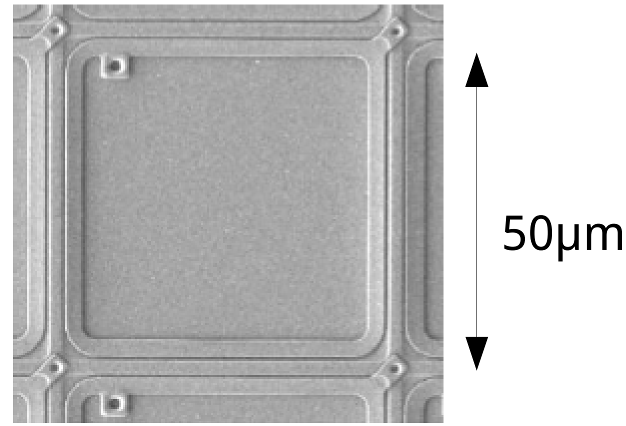


Breakdown probabilities > 90% are typical

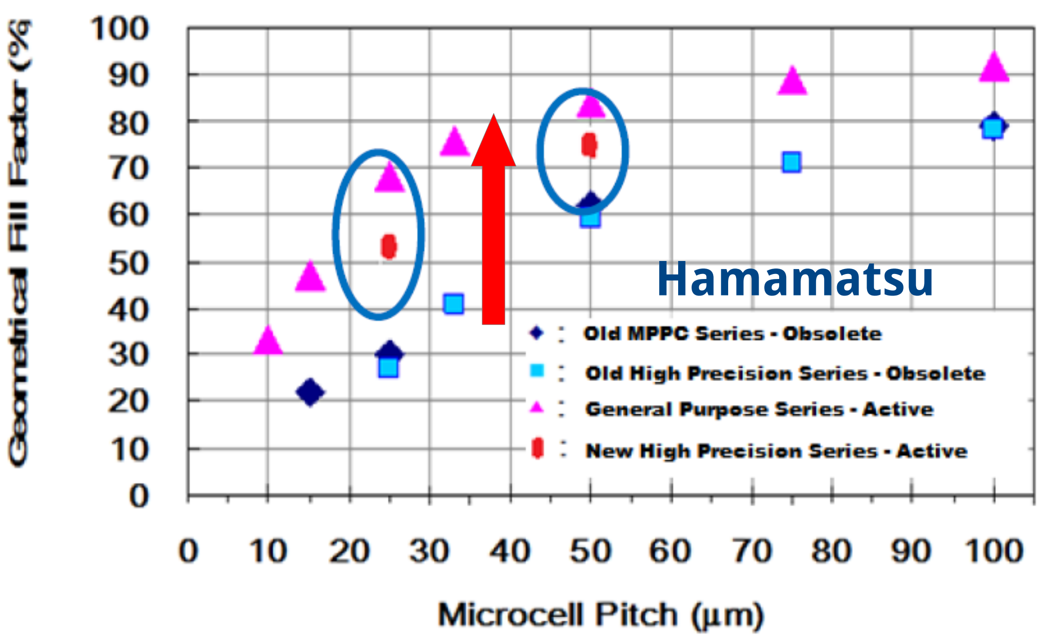
Geometrical Efficiency: Intra-Cell Spacing

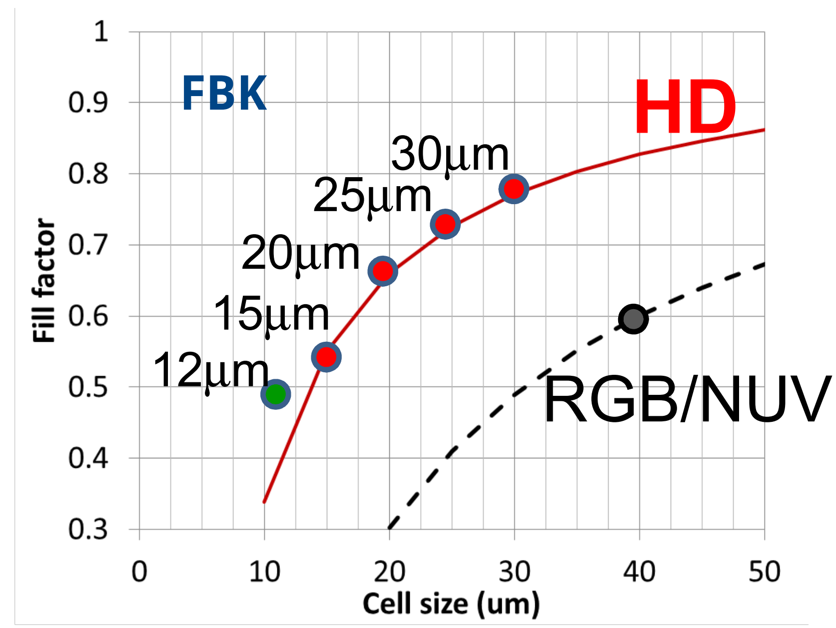


2004 MEPhI



2014 Hamamatsu





Geometrical efficiency ~80% are typical for 50 µm cells

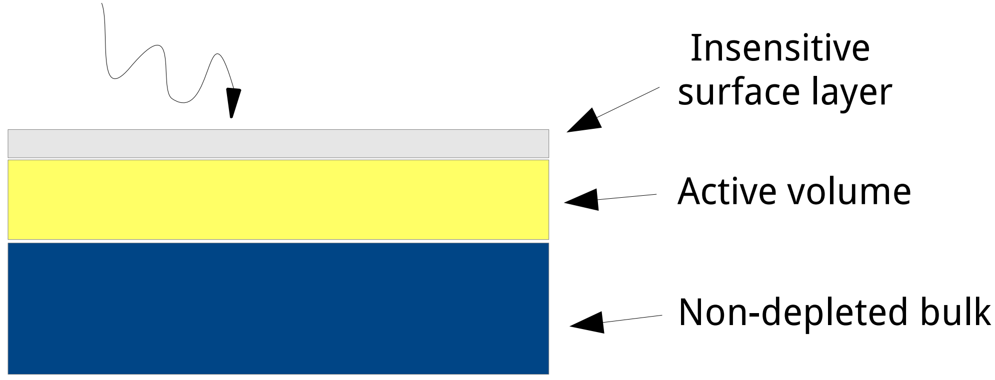
Effective Quantum Efficiency

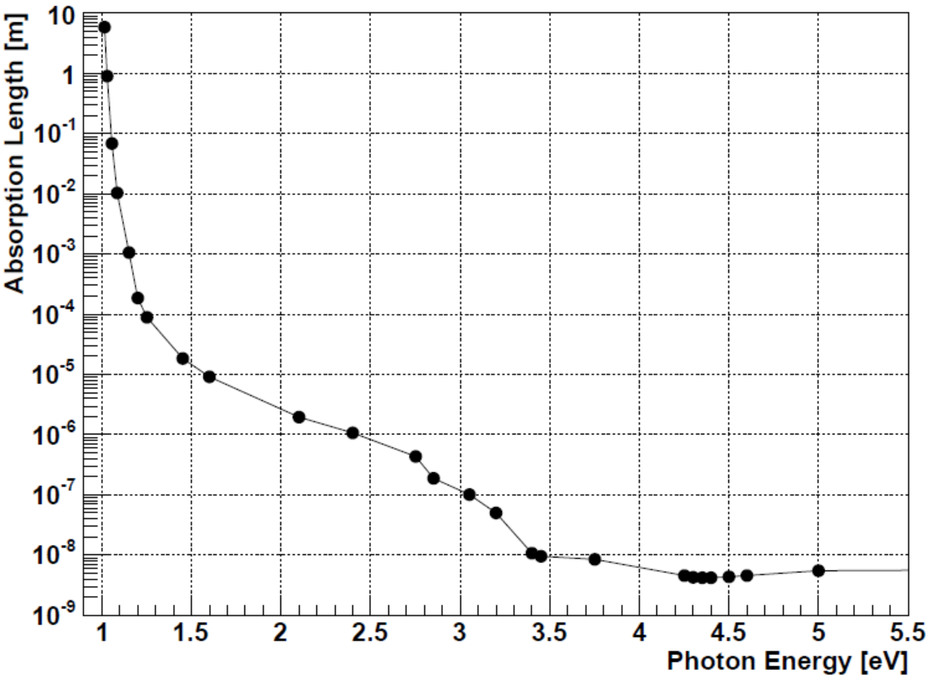
Probability that a photon gets absorbed in the device
AND that the electron or hole makes it into the avalanche region

For UV sensitivity (~100nm absorption length)
Thin, UV transparent entrance window
and
shallow first implant

For Red/IR (>1 μm absorption length):
thick depletion region

Plus anti reflective coating



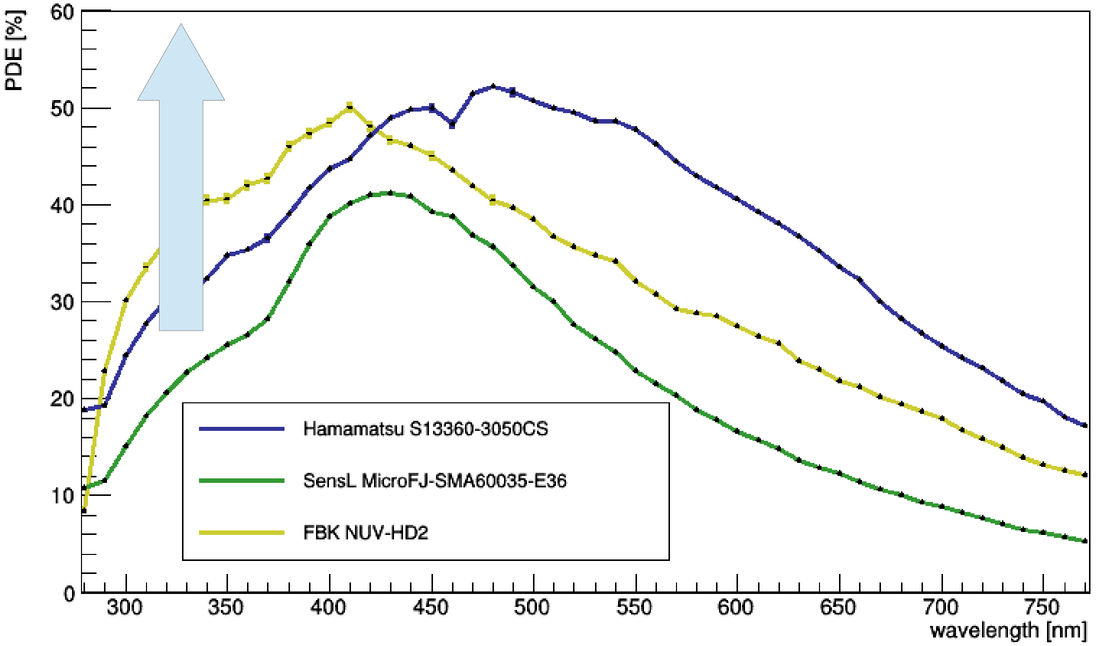


$$P_{abs}(x,l_{abs})=1-e^{-x/l\_abs}$$

Future Improvements of PDE

Peak PDE already close to maximum possible between 400 nm and 550 nm

0.9 B.P. * 0.8 G.E. * 0.9 QE = 0.65



Spectral response matches emission spectrum of most anorganic & organic scintillators

But below 400 nm ...

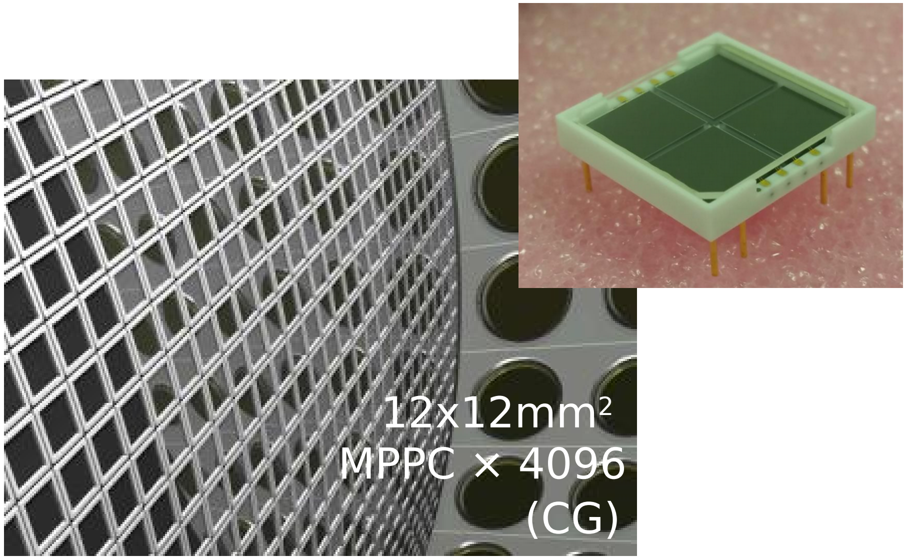
For Cherenkov light detection want better NUV sensitivity

UV transparent coating
thinner passivation layer
anti reflective coating

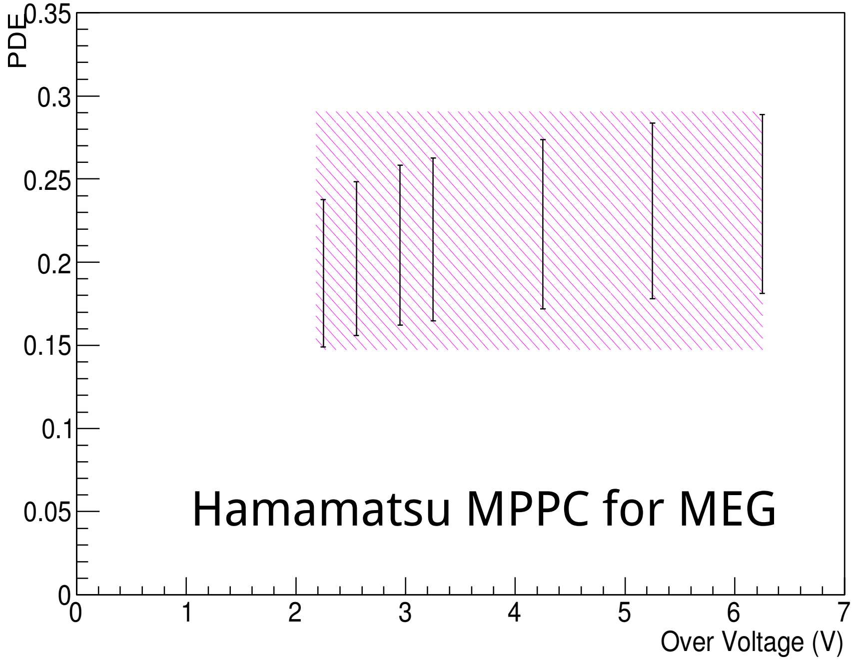
→ room for improvement 30% - 50%

Ultimate goal is to have response curves tailored for different applications

SiPMs for Noble Liquid Detectors



Figures and pictures from Kei Ieki (MEG II Collaboration) (Pisa 2015)



Pushing into the VUV for the detection of scintillation light in Noble Liquids

130 nm, 180 nm

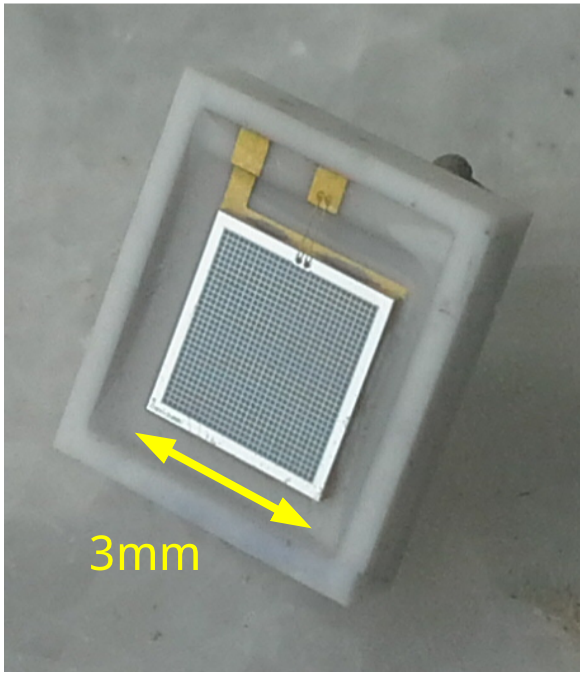
Increasing demand in HEP and dark- matter experiments

Dedicated development from Hamamatsu for MEG II yields 20% PDE @ 180 nm

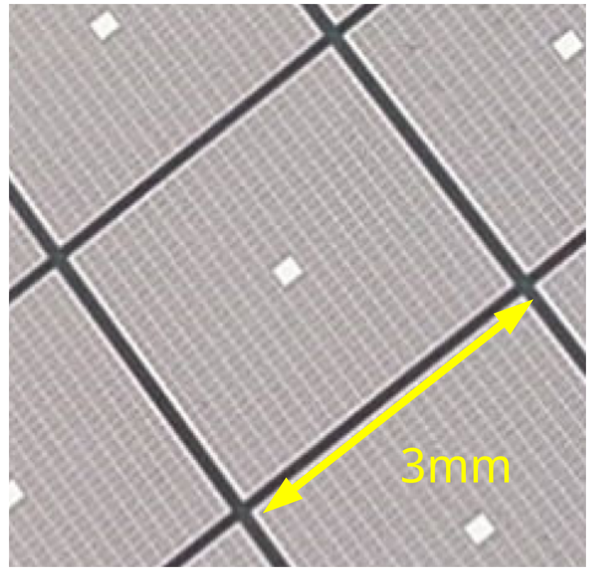
Hamamatsu S10943-3186(X)

Could be improved further

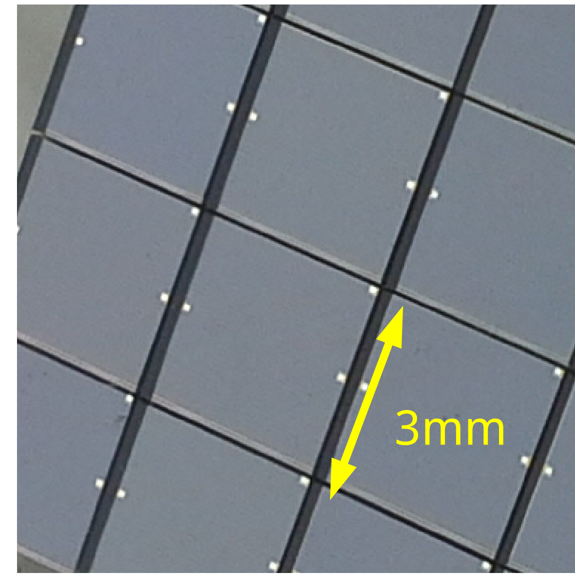
Packaging
Minimizing Dead Space between SiPMs



Hamamatsu 2008



Hamamatsu



SensL

Elimination of bond wires with through silicon vias

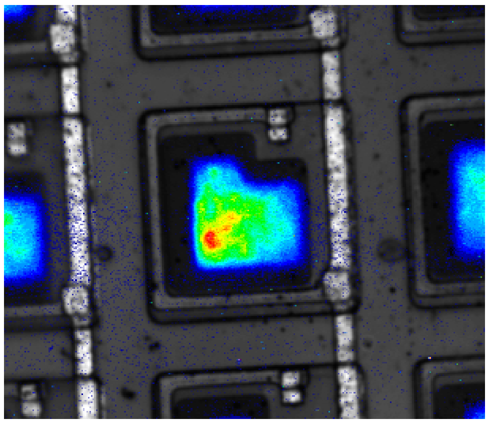
thinner guard ring around device

Chip packaging with much reduced gaps between chips
0.1 to 0.2 mm gap possible between chips → **>90% efficiency**

The pragmatic and cost-effective approach to arrive at large sensor sizes

Let's talk about Nuissances

Optical Crosstalk



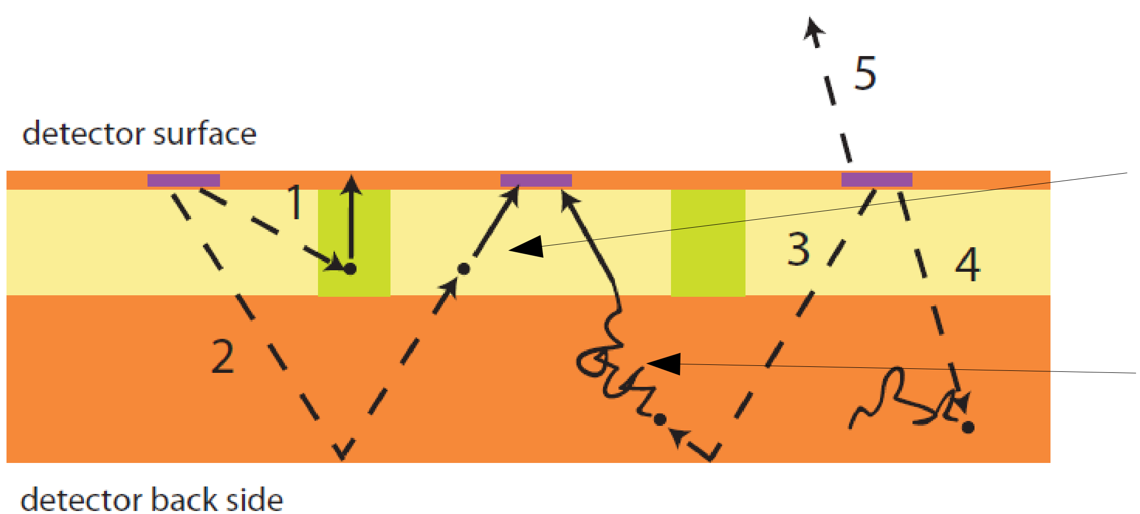
C. Merck

Photons are emitted during breakdown

Photon emission mechanism not well understood

Photons with λ = 900nm – 1100nm have the right absorption length to produce optical crosstalk

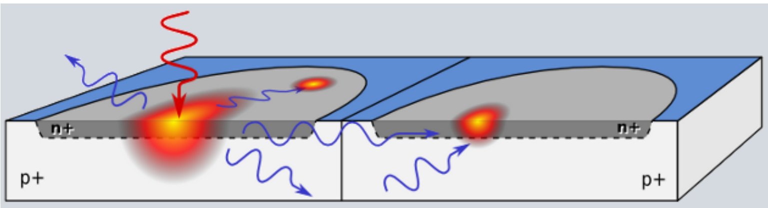
~$3 \cdot 10^{-5}$ photons per charge carrier in the breakdown



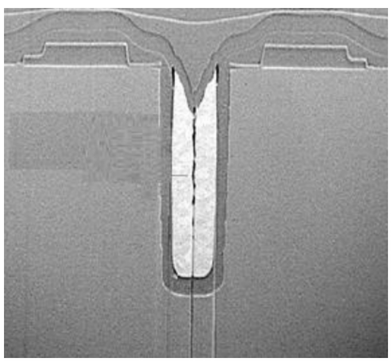
Direct optical crosstalk
Instantaneous <<1ns
→ pile up of signals

Indirect optical crosstalk
Delayed 10 - 100 ns
→ contribution to afterpulsing and effective dark rate

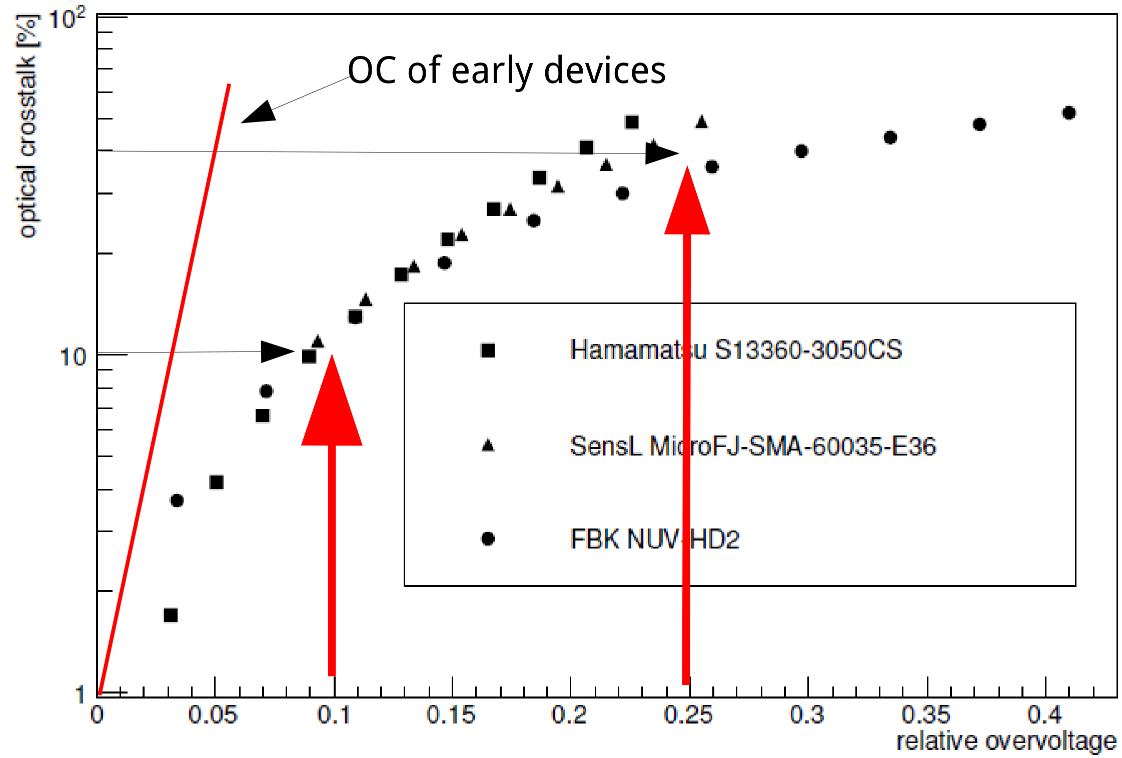
Direct Optical Crosstalk



Rech (2008)



Hamamatsu

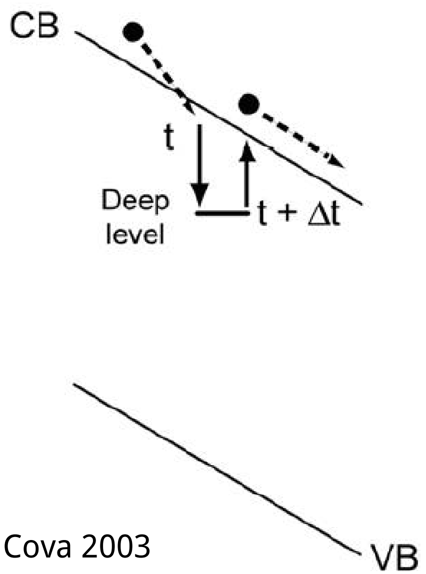


Trenches to suppress OC

10% - 40% optical crosstalk
when operating at 90% breakdown probability

What about treating the back side to absorb crosstalk photons?

Afterpulsing



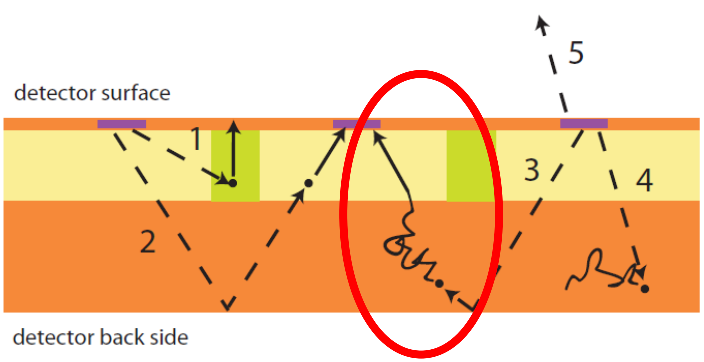
Cova 2003

Two contributions

Delayed release of trapped charge carrier
→ breakdown of the same cell

proportional to gain (ΔU) (filling traps)
and
breakdown probability (1-exp(-ΔU(t)/A))
(detecting released trapped carriers)

Solution: improvements in technology

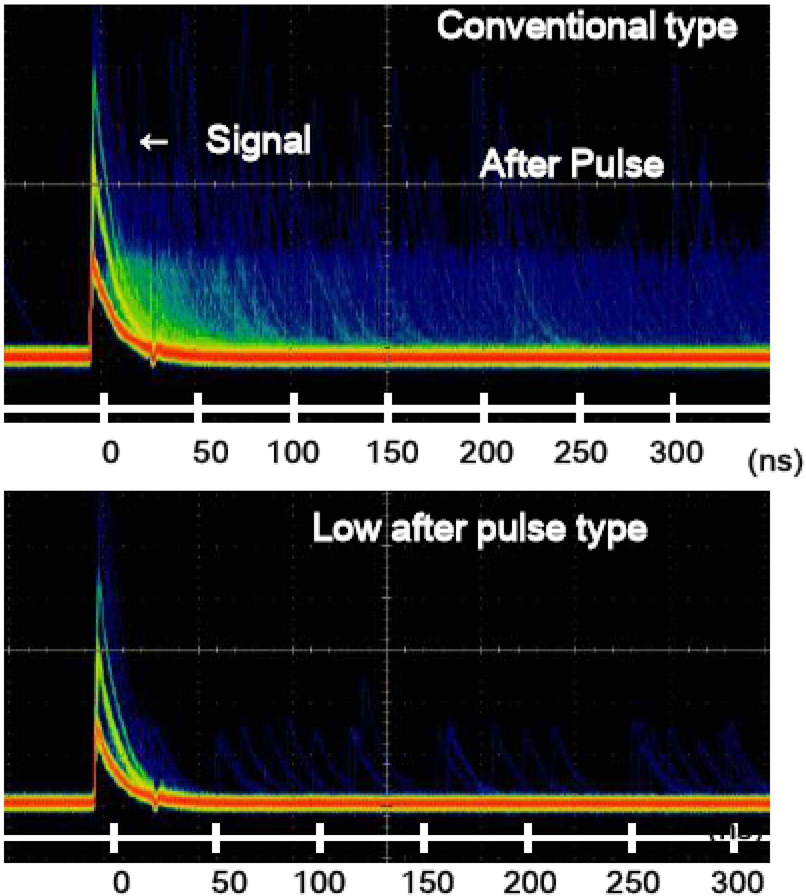


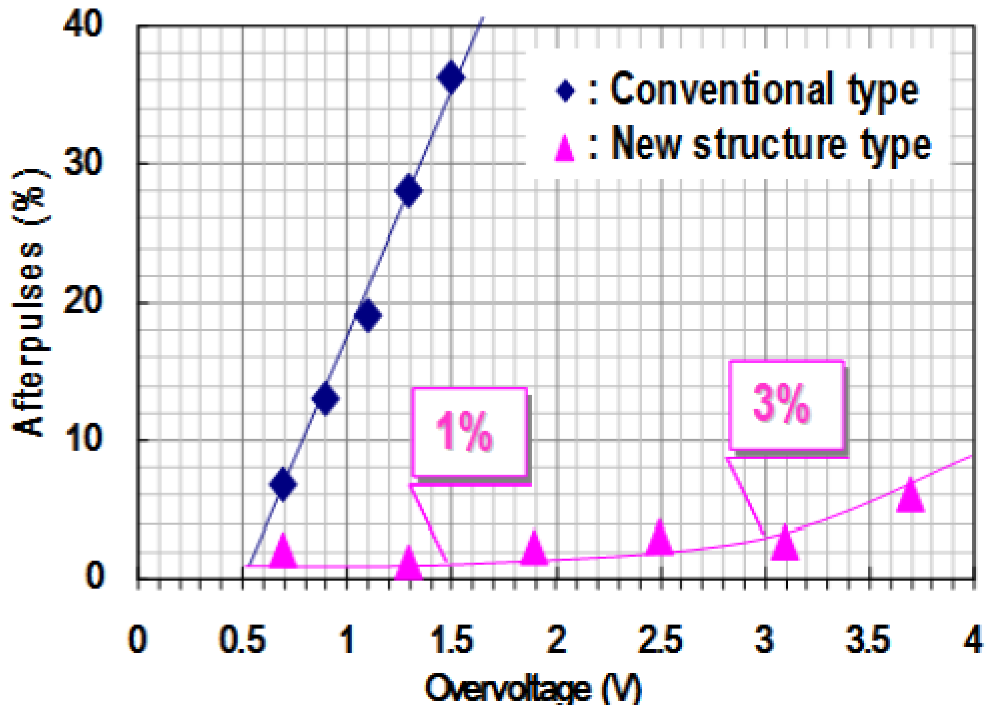
Delayed optical crosstalk photons
→ breakdown of a neighboring cell

Solution: potential barrier between epitaxial layer and bulk

Also lower gain would help

Noise Reduction – Afterpulse for General Purpose and High Precision





After pulse probability has been suppressed by optimization of structure and material.

All new MPPC series have very lower after pulses compared with conventional type.

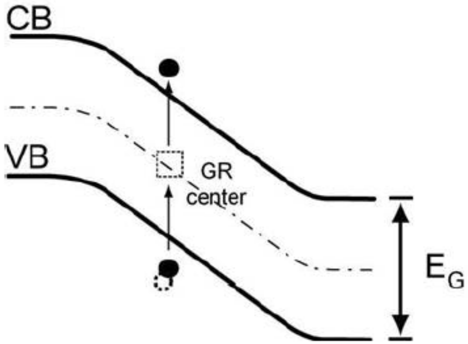
Slide from Hamamatsu

also see K. Sato (2013)

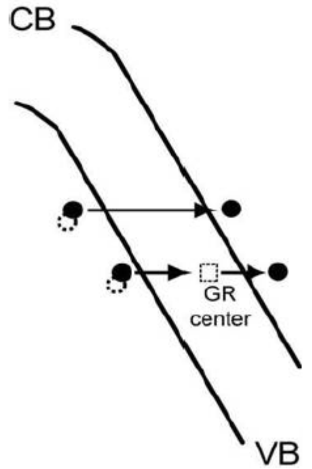
Effective Dark Rates

Contributions

1. thermal generated
2. tunneling
3. afterpulsing

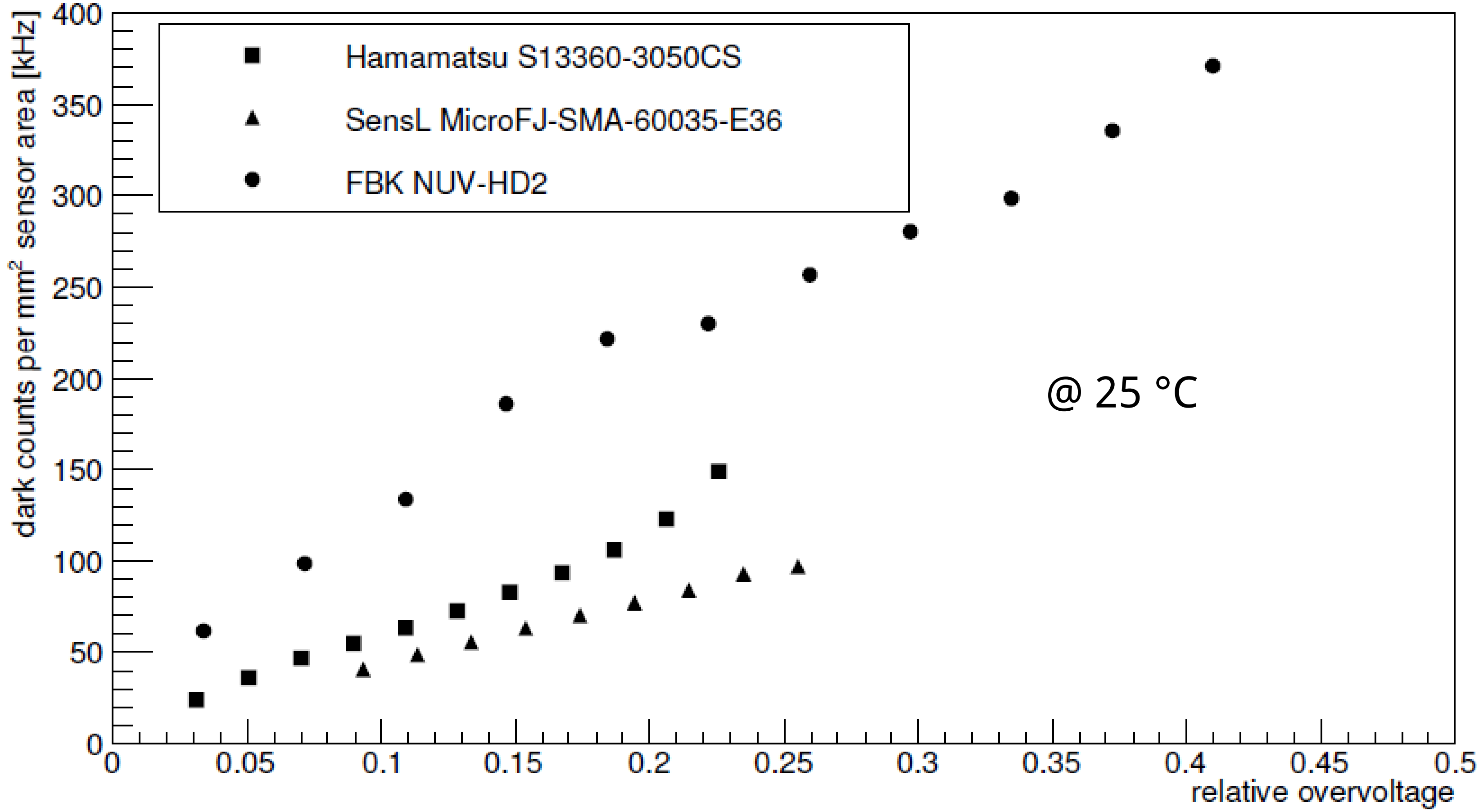


Generation - Recombination Centers



Field-Assisted Generation

Dark Count Rates



Sub 100 kHz/mm² is the new standard

Sub 50 kHz/mm² standard in reach

Achieved already by SensL, Hamamatsu, …

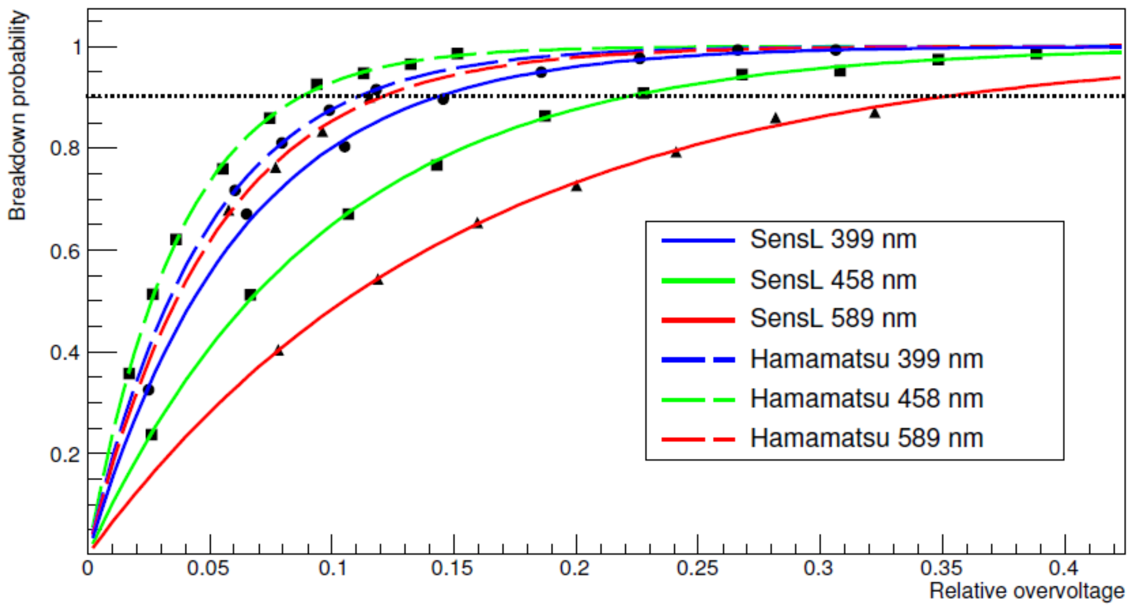
And of course cooling will lower dark count rates if needed

Gain & PDE Dependence on Temperature

Breakdown voltage increases typically by 0.01 %/°C

$\Delta G/G = 0.01\%//°C * 1/V_{\text{rel over}}$

→ temperature effects decrease with increasing overvoltage



Present generation can operate at 10% to 30% relative overvoltages

For 10% relative overvoltage → 0.1% gain change per °C

For 30% relative overvoltage → 0.03% gain change per °C

The change in PDE is even less because the breakdown probability is in saturation

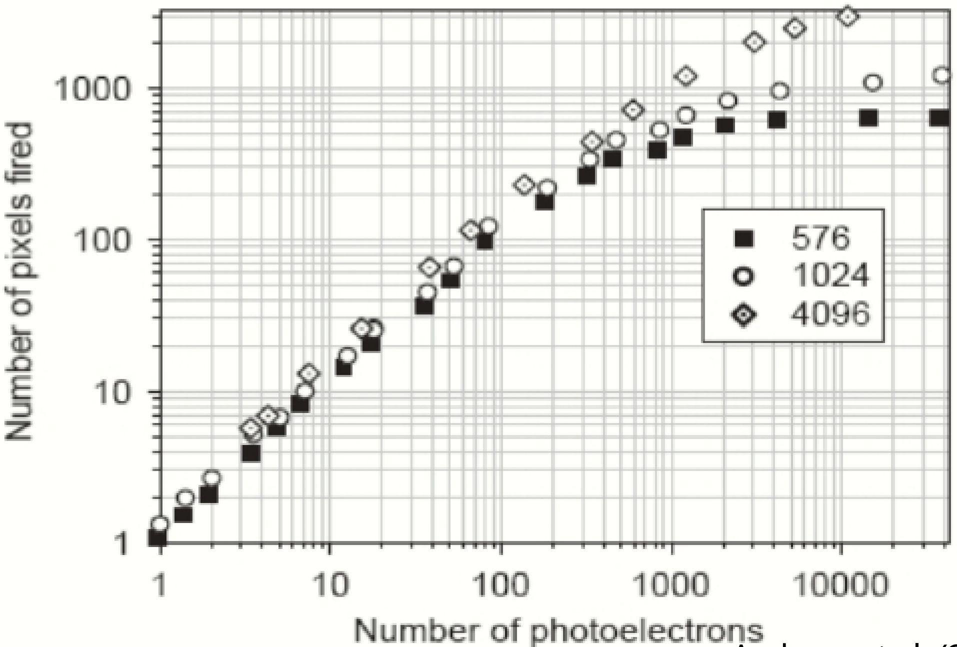
Compare to 0.1 % to 0.2 % change in QE per °C for PMTs

(Burle/Hamamatsu photomultiplier handbook)

Dynamic Range

Finite number of cells dictates dynamic range

$$N_{\text{fired}} = N_{\text{cells}} \left[1 - e^{-\frac{N_{\text{phe}}}{N_{\text{cells}}}} \right]$$



Andreev et al. (2005)

Note that behavior changes for large number of photons

L. Gruber, et al., *Over saturation behavior of SiPMs at high photon exposure*, *NIM A*, **737** 1118 (2014).

A limiting factor of the energy resolution in calorimetry:

→ developments of SiPMs with small cell sizes < 10 μm by FBK, Hamamatsu, and Ketek

→ increases dynamic range x 100

Radiation Hardness

Minimize effects due to increase in dark rates and shift in breakdown voltage

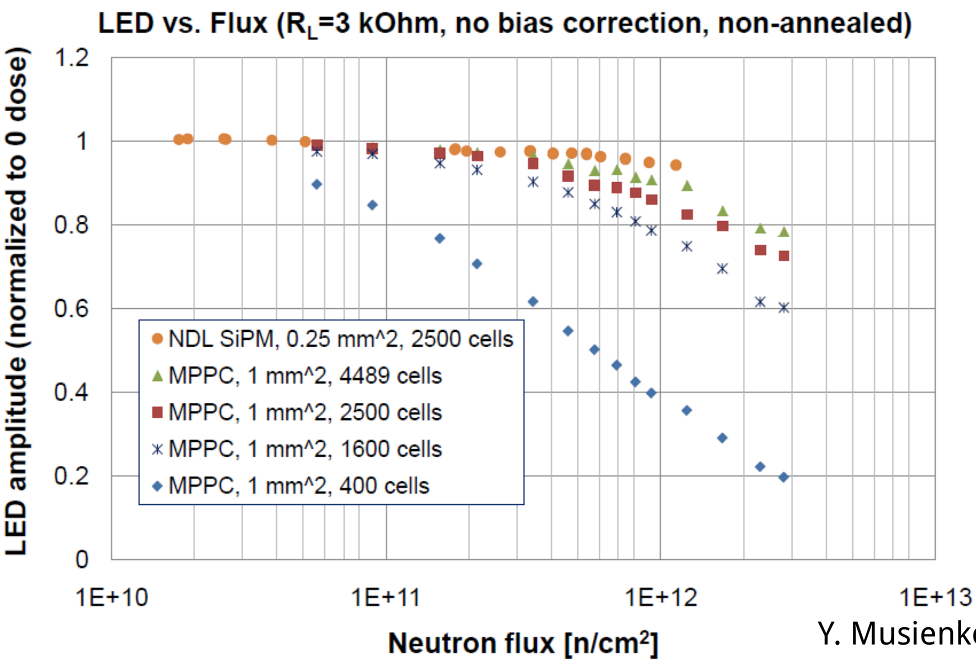
- Small cell sizes to reduce dark count rate per cell
- Reduce recovery time to <10ns
- Low active volume to reduce dark count rate

Extensive successful R&D efforts for CMS upgrade over the past years

- Dynamic range: > 20 000 "effective" cells/SiPM
- Cell recovery time: <10 ns
- Dark current (T=24 °C, after $2*10^{12}$ n/cm^2): <1000 μA
- Fractional Gain*PDE (after $2*10^{12}$ n/cm^2): >65%
- Neutron sensitivity: low

Possible to achieve 10^{14} n/cm^2 required for SLHC Phase II HCAL upgrade of CMS?

R&D programs have started



Y. Musienko

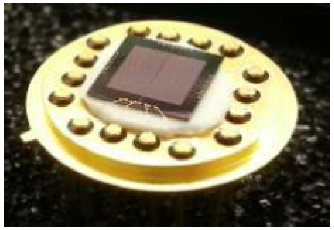
Georgia Tech

Solid State Photomultipliers

different semiconductor materials SiC, InGaAs, GaAs, GaInP

LightSpin
Princeton Lightwave
GE global research
...

Packaged SiC SSPM



Active area: 4x4 mm²
Pixel size: 60 um
16 sub arrays
Area of sub-array:
1x1 mm²

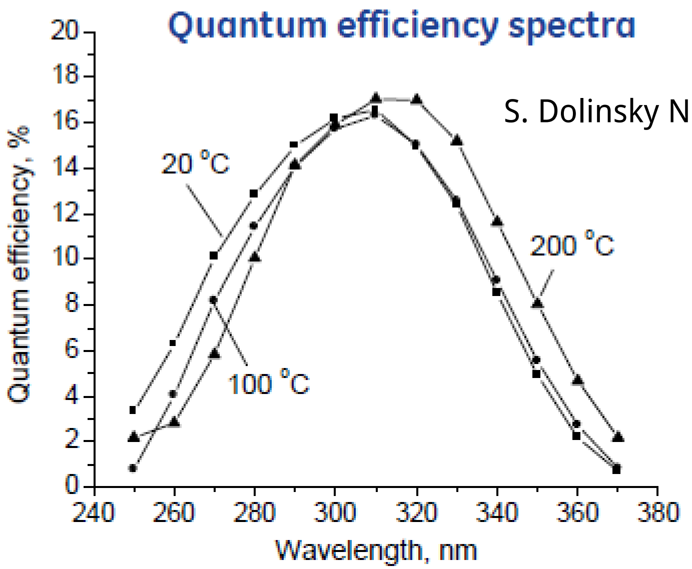
Advantages:
Adjustable bandgap
→ engineered spectral response

Better radiation hardness

High temperature applications

Lower dark count rates

A technological challenge



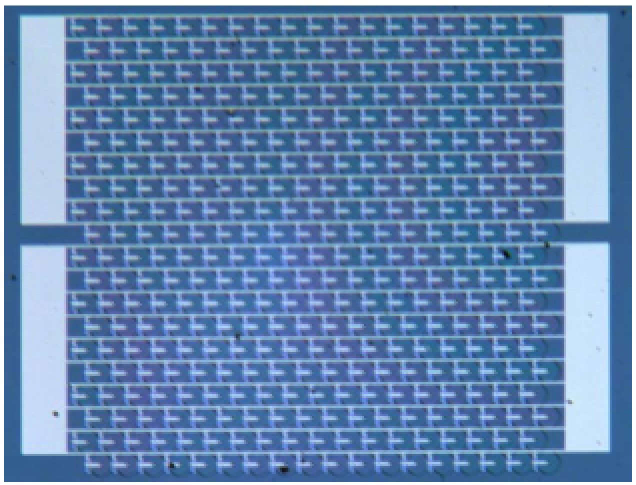
GaAs SSPM

LightSpin's GaAs Photomultiplier Chip™

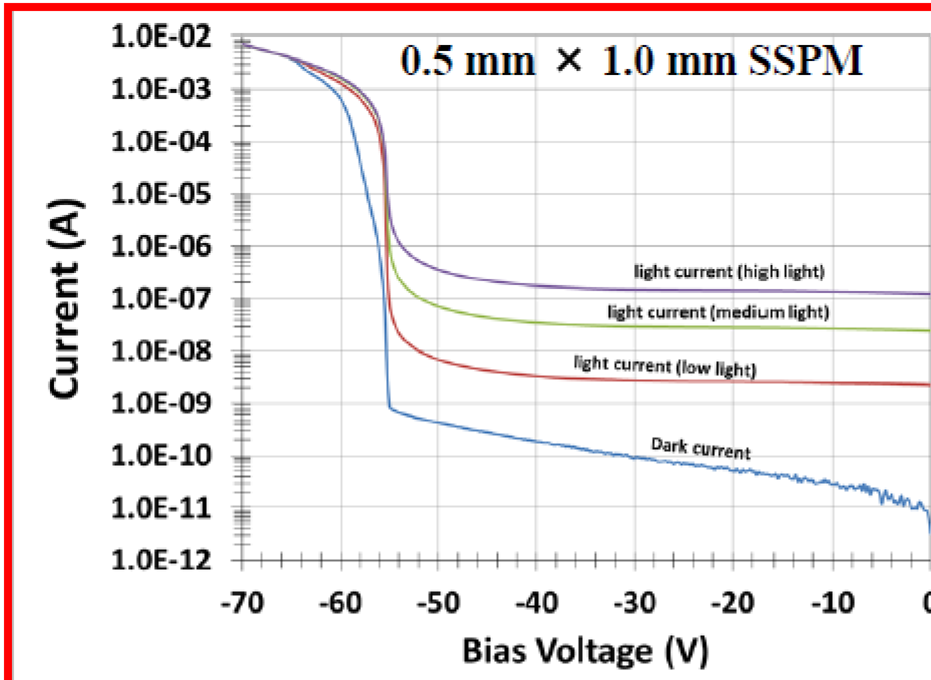
Developed for the CMS HCAL Upgrade Phase II Project:

UNIVERSITY of VIRGINIA

LightSpin Technologies, Inc.



Array of single-photon avalanche devices (SPADs): 2x0.5mmx1 mm, 360 SPADs/mm^2



E_g(GaAs)~1.4 eV (E_g(Si)~1.1 eV) → potentially smaller DC after irradiation? Very high electron mobility → fast timing?

Slide from Yuri Musienko

Discussion

SiPMs have become a versatile tool in HEP, astroparticle physics, medical imaging, ...

Improving existing applications and enabling new applications

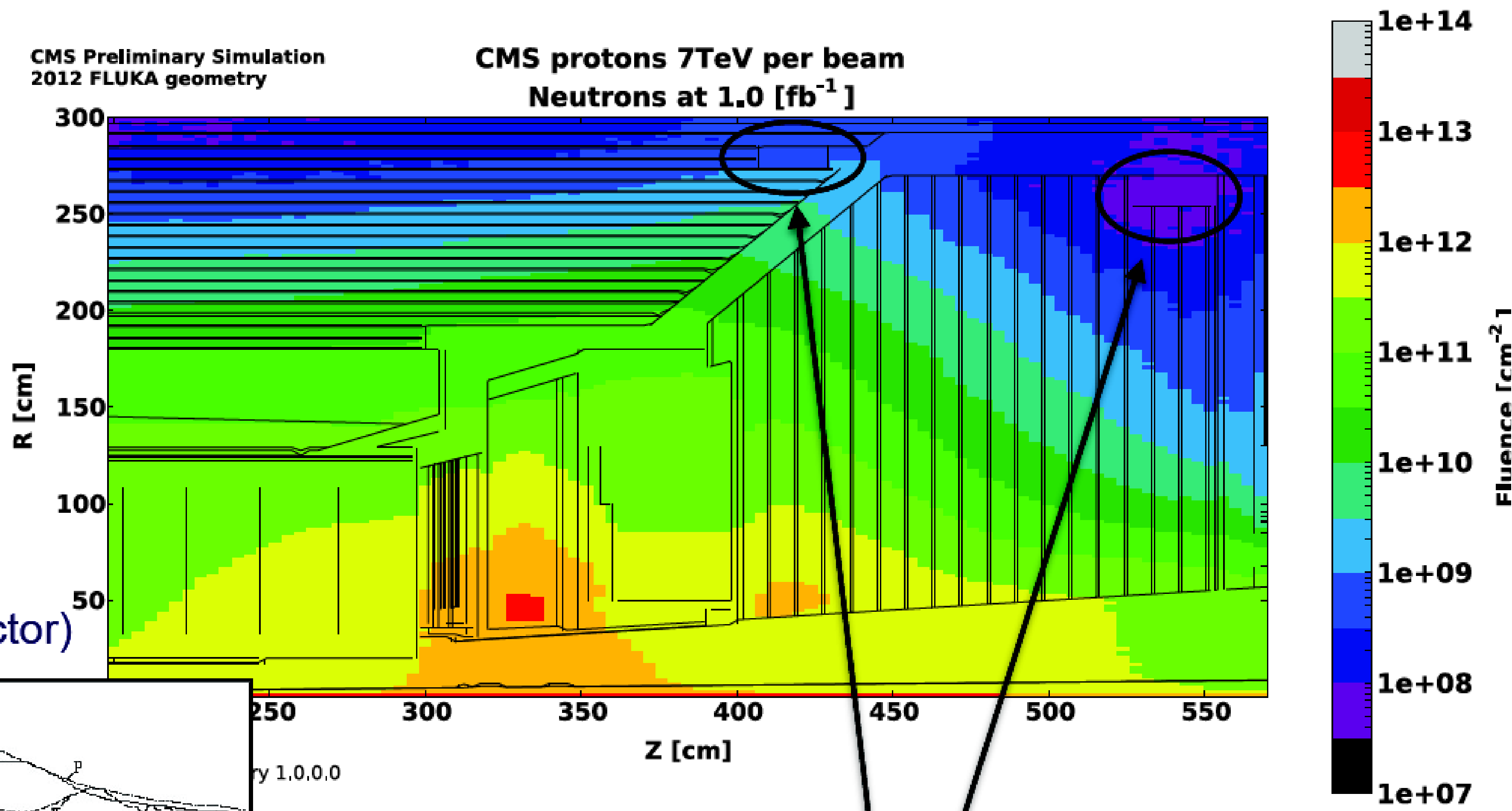
- Huge advances made over the past ten years
  - Peak PDEs > 50%
  - Dark Count rates ~ 50 kHz/mm^2
  - Low optical crosstalk and afterpulsing

- Still room for improvement possible for some applications
  - Better UV sensitivity for Cherenkov <400nm
  - Better VUV sensitivity for liquid noble detectors 128 nm, 178 nm
  - Radiation hard SiPMs – up to 10^{14} n/cm^2?
  - Dark count rates < 50 kHz/mm^2 at room temperatures?
  - Lower optical crosstalk?
  - Smaller cell sizes
  - Lower gain
  - Costs of << 1 \$/mm^2

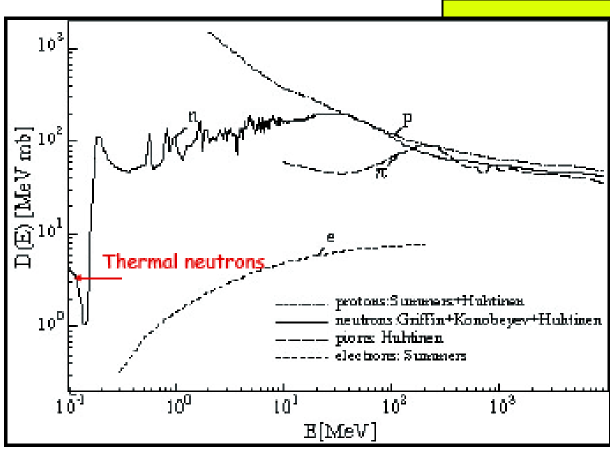
- Development of solid-state photomultipliers (non silicon based) has potential

- Intergration of readout into SiPMs following the path of the digital SiPM and 3D SiPM

End



(Si - NIEL factor)



Currently Approved SiPM installation for max 10^{12} n/cm^2
1 Mev eq. for a CMS total integrated luminosity of **3000 fb^{-1}**

MORE R&D needed to achieve development of SiPMs capable of operating closer to the beam pipe

Summary of Key SiPM Parameters

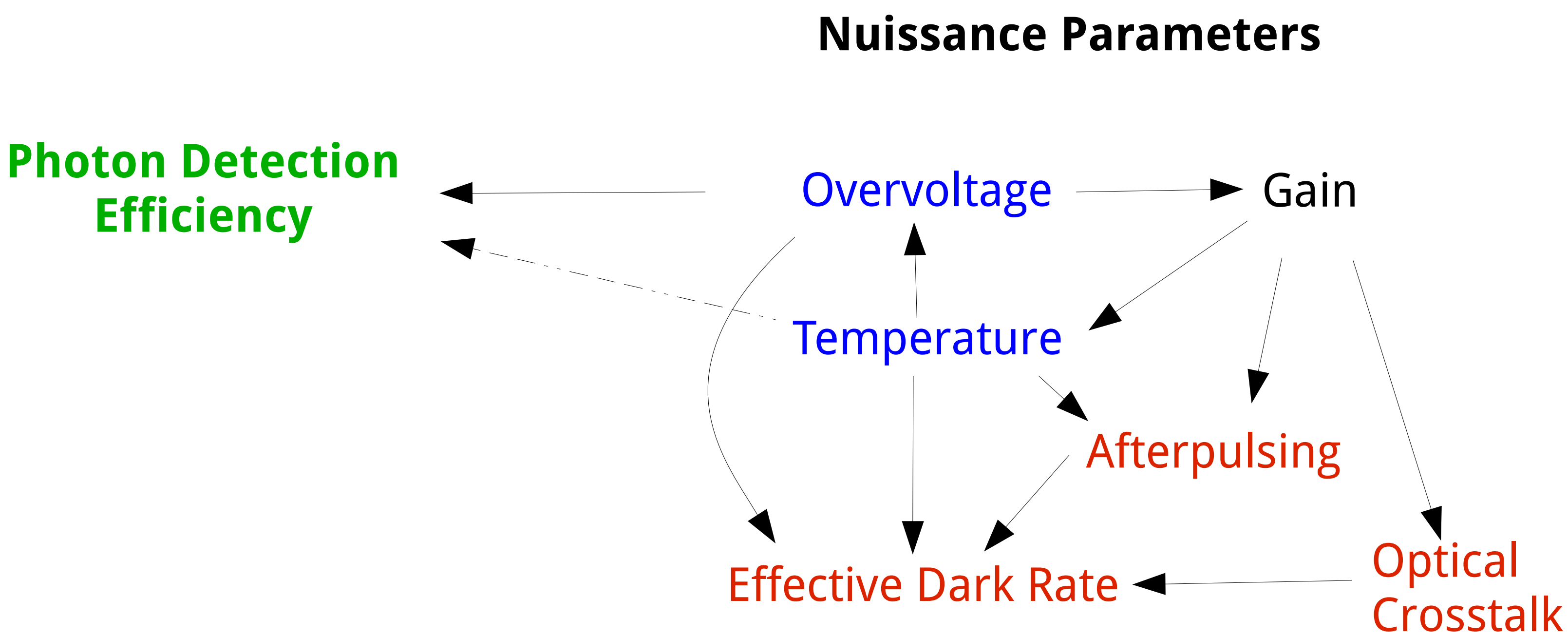
Parameter	2005	Now	Wish List
Spectral Response	Green Sensitive **n-on-p structure**	Blue and Green **p-on-n structure**	Tailored to application
Photon Detection Efficiency	~10%	~45%	>70%
Dark Noise	1MHz/mm^2	<100kHz/mm^2	As low as possible
Optical Crosstalk	>20%	<10%	As low as possible
Afterpulsing	>20%	<1%	As low as possible
Sensor Size	1mm^2	1mm^2-36mm^2	

SiPMs are ready for prime time

due to rapid improvements in the past 10 years

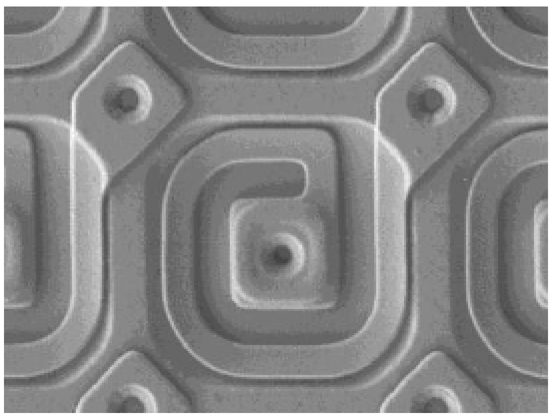
SiPM Parameters

User's perspective



Transparent quench resistors

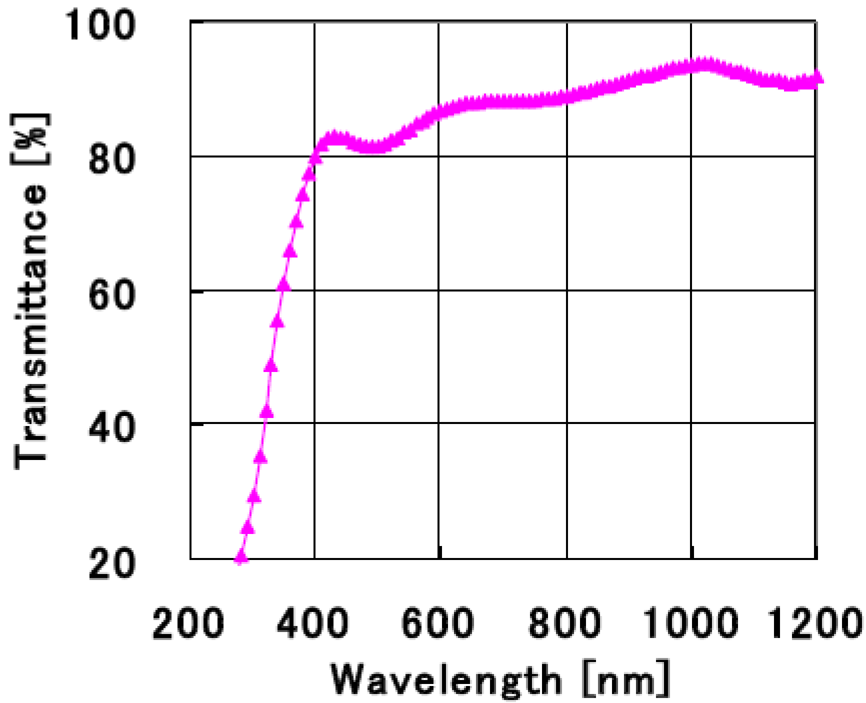
Metal film resistors



10µm cells

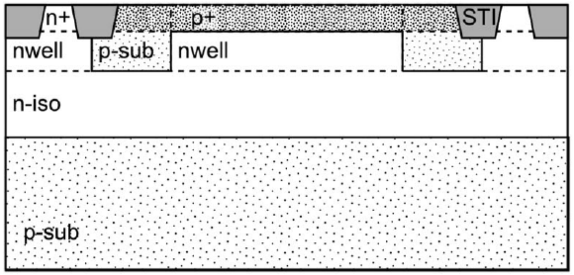
~30% fill factor

Allows much higher cell densities

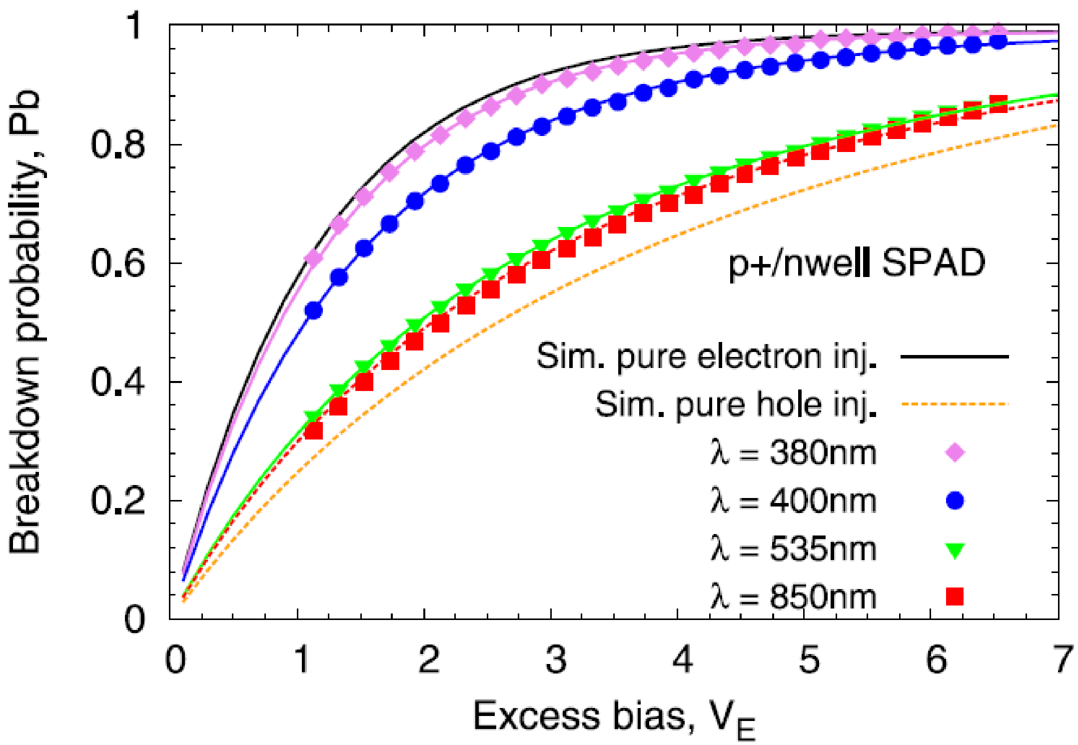


Hamamatsu

Breakdown Probability vs. Bias



Pancheri et al (2014)



p-on-n structures
needed for UV sensitivity

→ electron initiated breakdown

Parameterization of Breakdown Probability

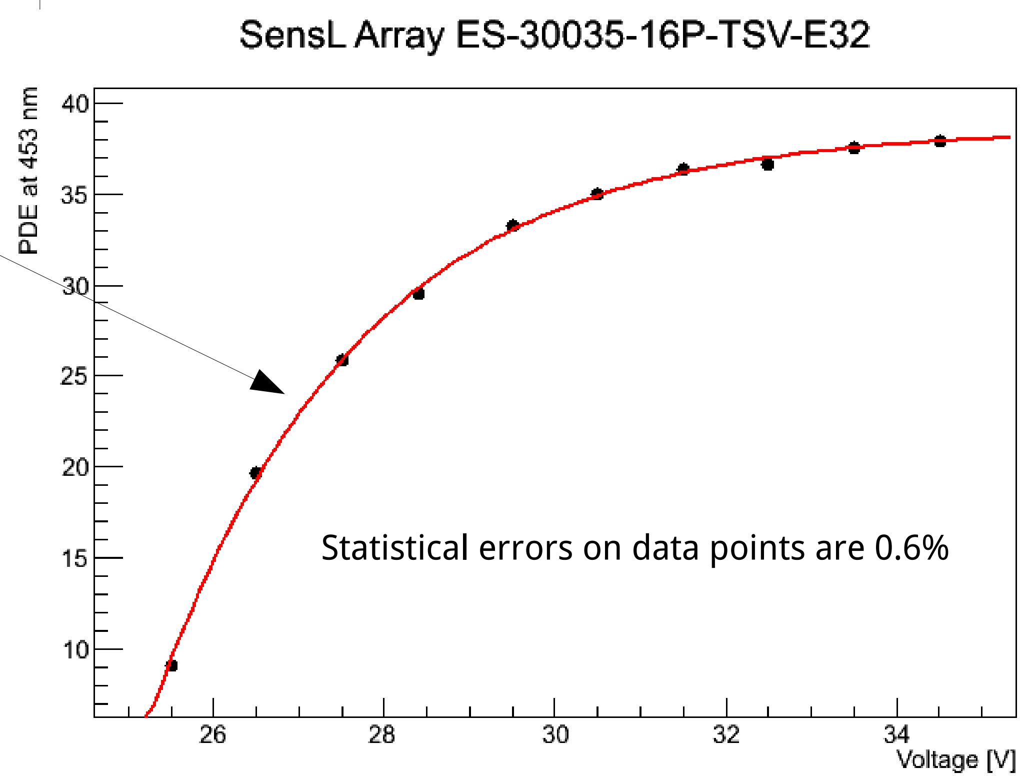
$$PDE(U) = PDE_{max} \cdot \left[1 - e^{\frac{-(U - U_{Break})}{\alpha\, U_{Break}}} \right]$$

This is a perfect fit of the data!!

Three free parameters:

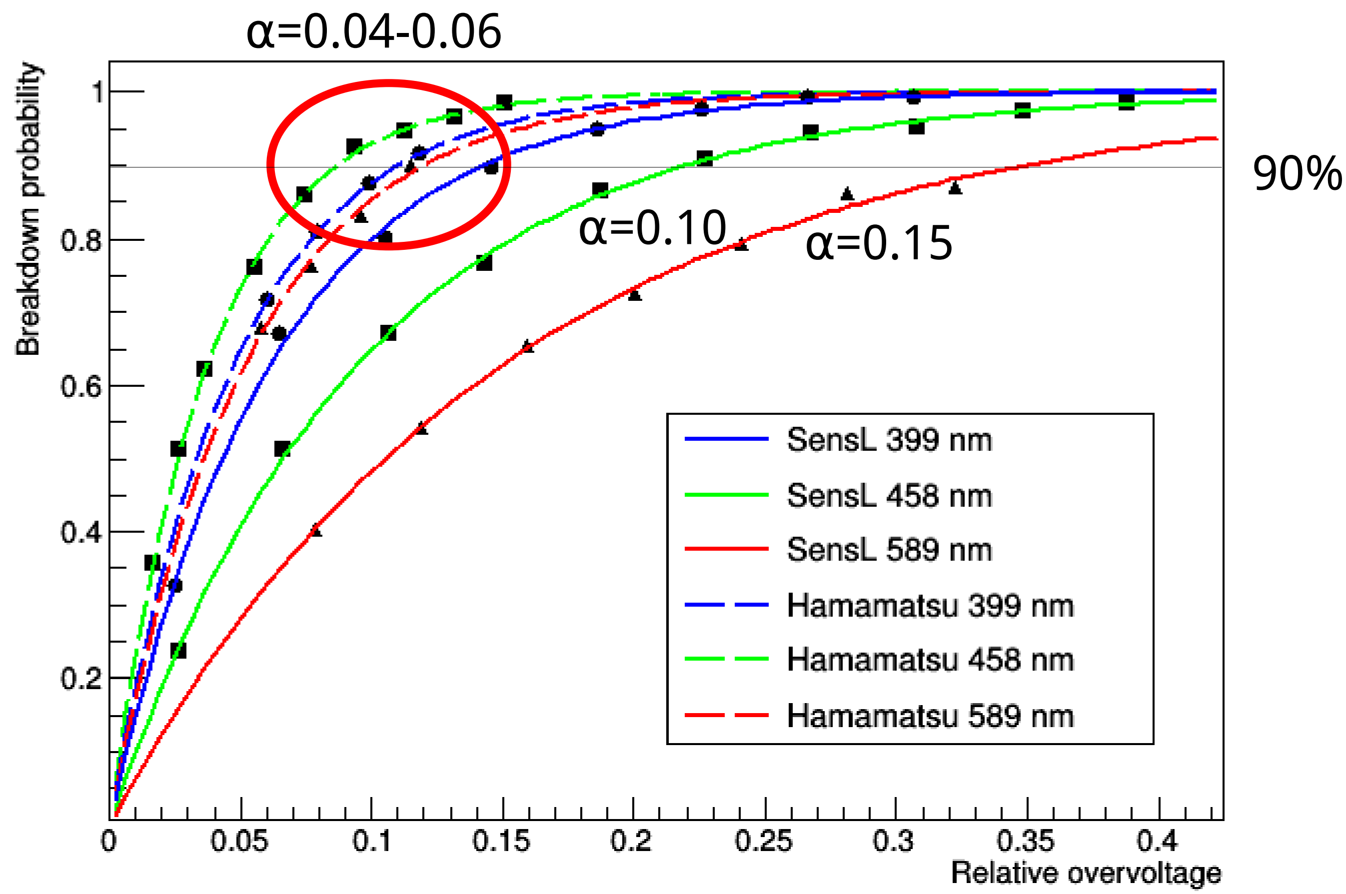
- Maximum PDE
- Breakdown voltage
- Constant α

All the physics of the breakdown probability is in α



Different Devices and Wavelengths

$$PDE(U) = PDE_{max} \cdot \left[1 - e^{\frac{-(U-U_{Break})}{\alpha\, U_{Break}}}\right]$$



To compare devices

Plot breakdown prob. vs. Relative overvoltage x

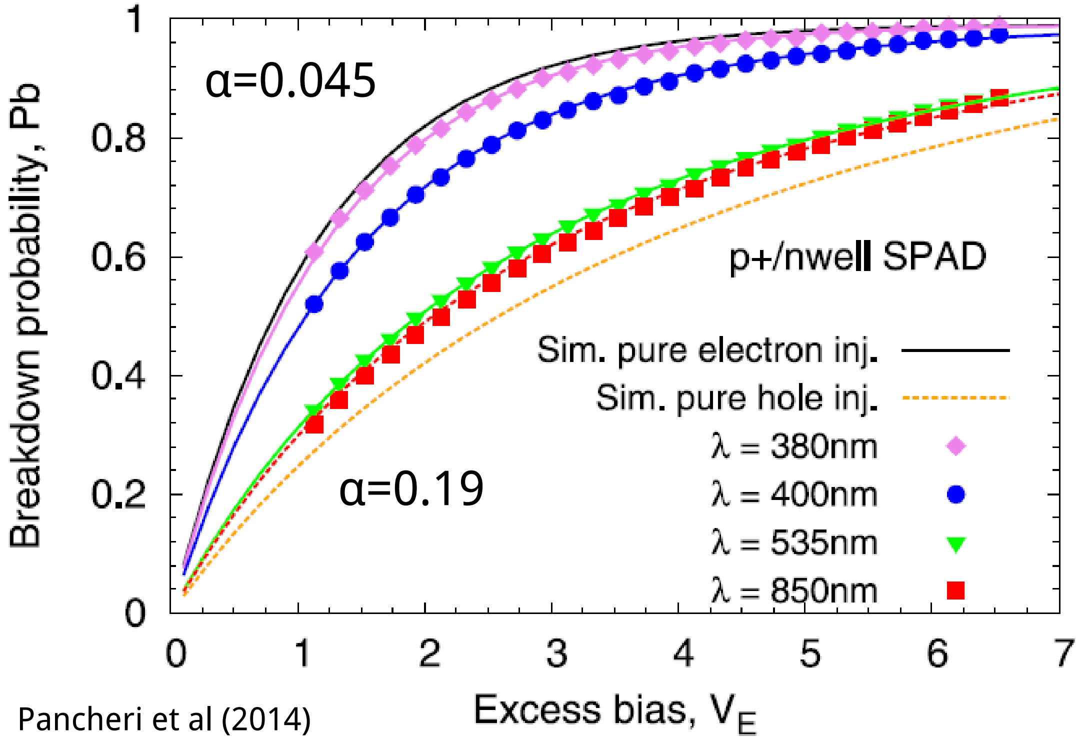
$$Breakdown\ Probability\,(x) = 1 - e^{\frac{-x}{\alpha}}$$

Relative overvoltage = relative electric field above critical field

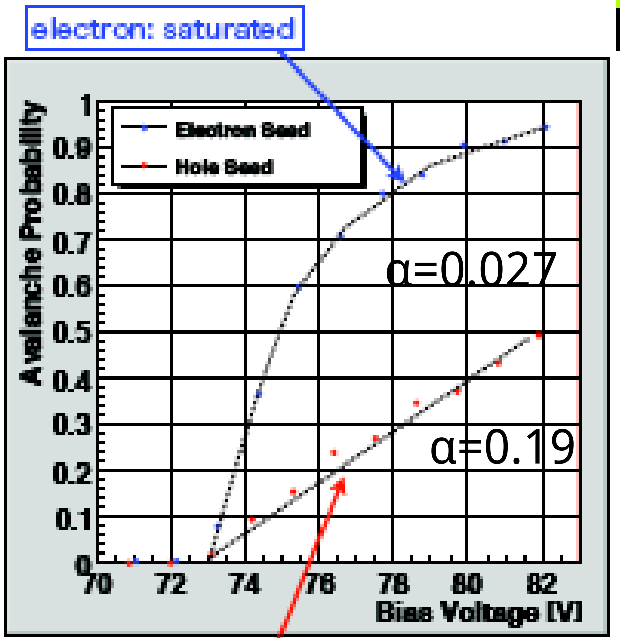
α is the only free parameter

Quite different α for the two devices and wavelengths, what is the difference?

Interpretation of alpha



Pancheri et al (2014)



H. Otono, et al., PANIC08

α ~ 0.03-0.05 pure electron injected
α ~ 0.2 pure hole injected

Looks like α does not strongly depend on technology

→ α can be used to reverse engineer avalanche structure :)

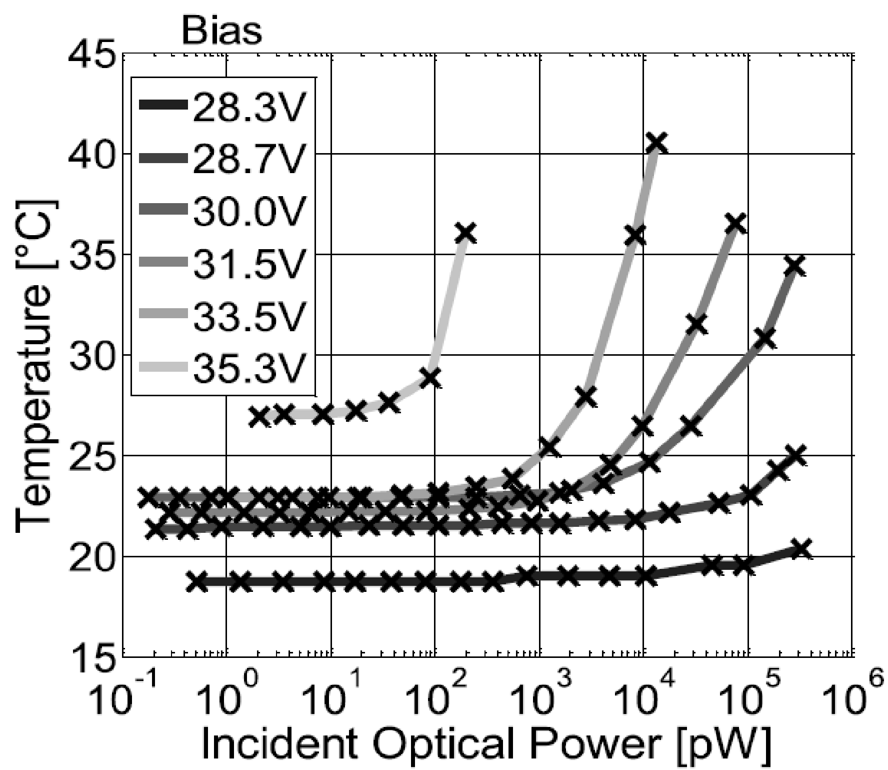
Gain and Temperature

SiPMs are considered low power devices

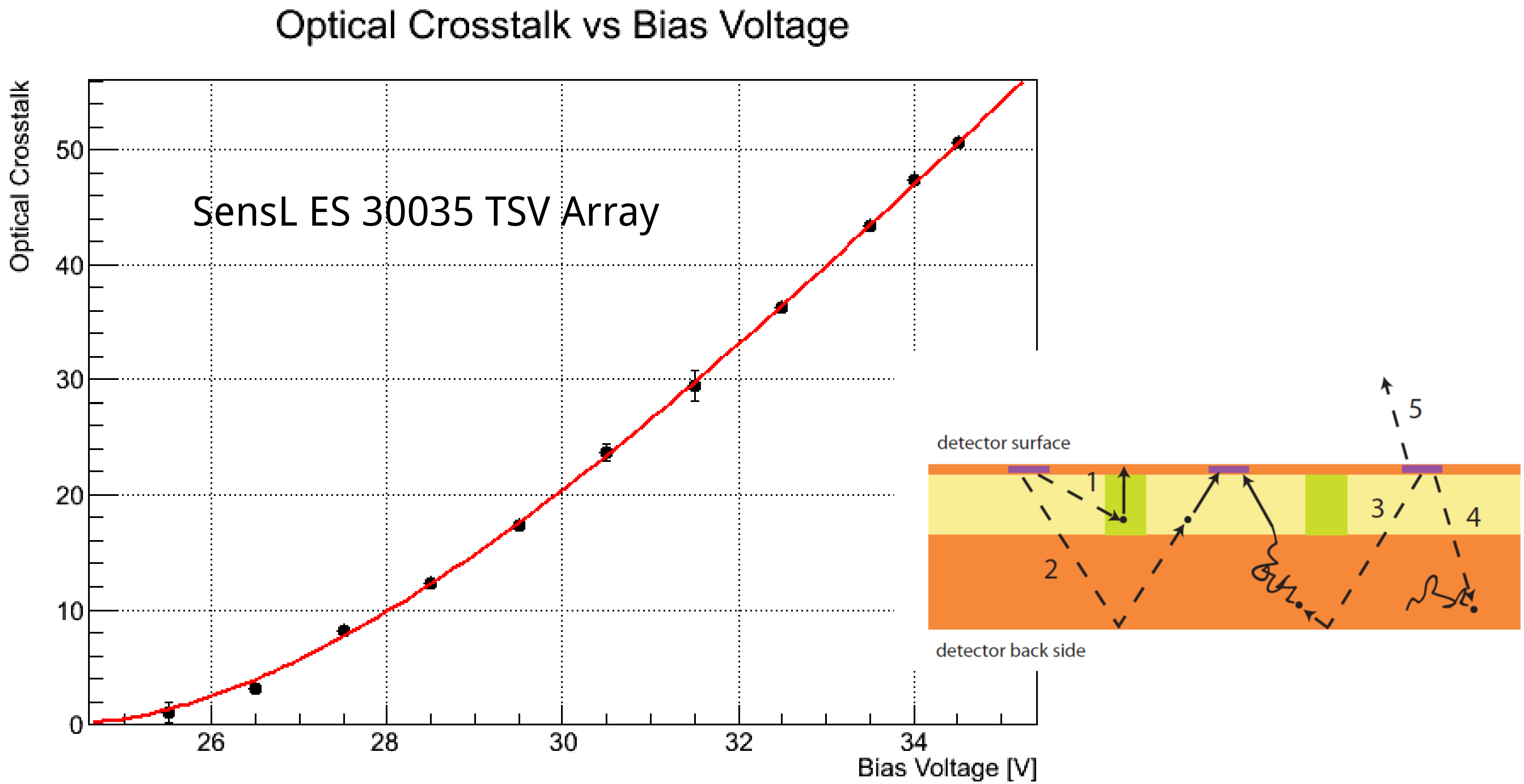
But operation in high background environments can dramatically increase temperature

→ Temperature management can become a problem and needs dedicated application specific solutions

Where are devices with small effective cell capacitances?



Adamo et al. 2013



A model to fit optical crosstalk vs. bias voltage

$\Delta G/\Delta U*(U-U_{break})*\varepsilon$ * $OC_{transmission}$ * $1-\exp[-(U-U_{break})/(U_{break}*\alpha)]$

Photons produced during breakdown

$\varepsilon=3*10^{-5}$ photons/charge carrier

Optical crosstalk transmission factor

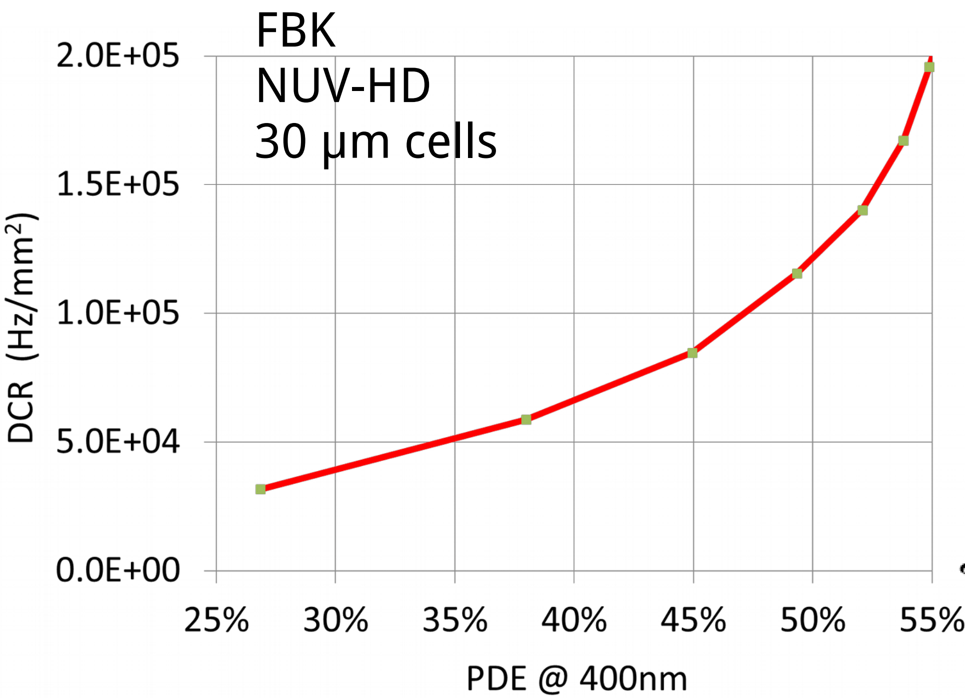
$OC_{transmission}=0.48$

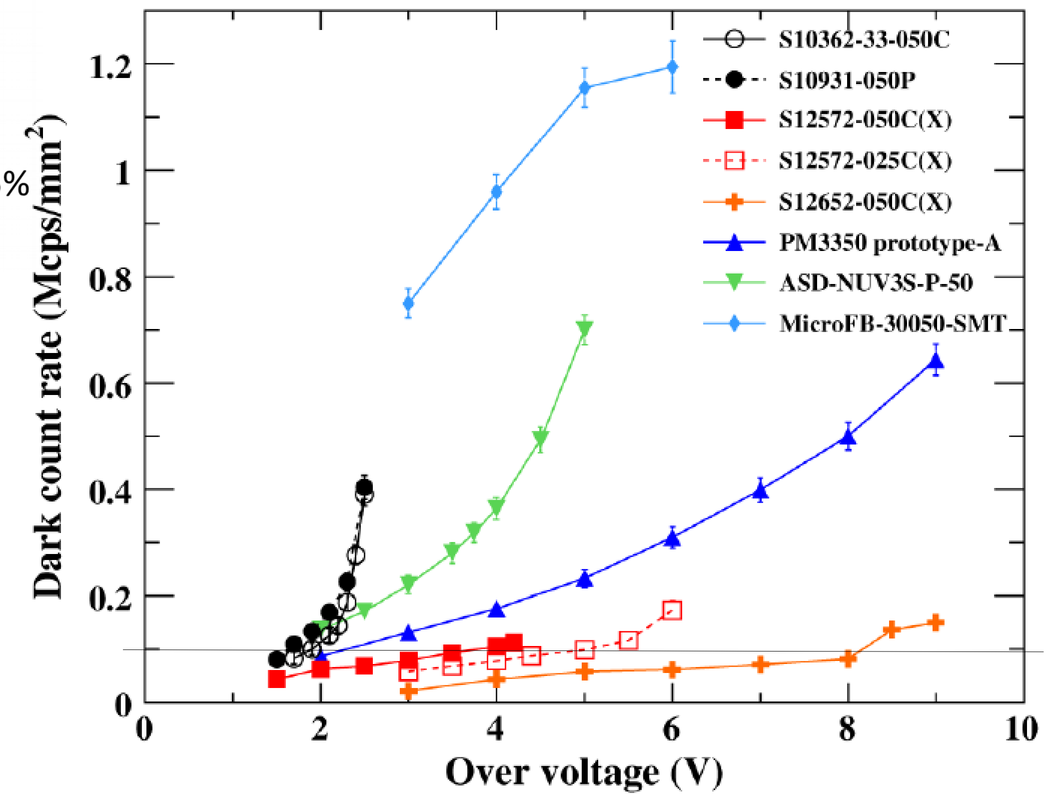
Breakdown probability

$\alpha=0.31\pm0.07$

Pure hole injected

Dark Rate Measurements at Room Temp.





Cattaneo et al. (2014)

Sub 100 kHz/mm² is the new standard

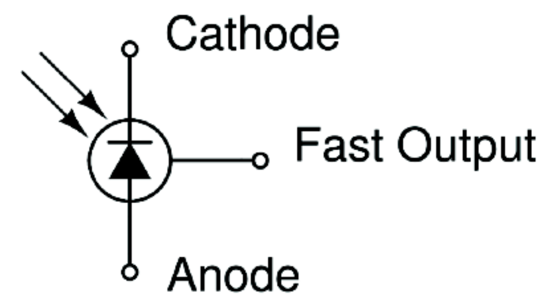
Sub 50 kHz/mm² standard in reach

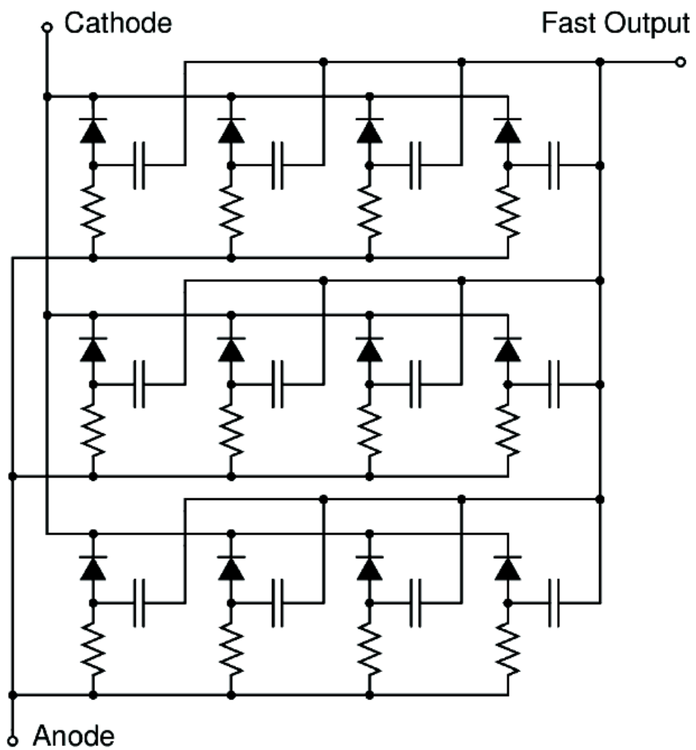
Achieved already by SensL, Hamamatsu, …

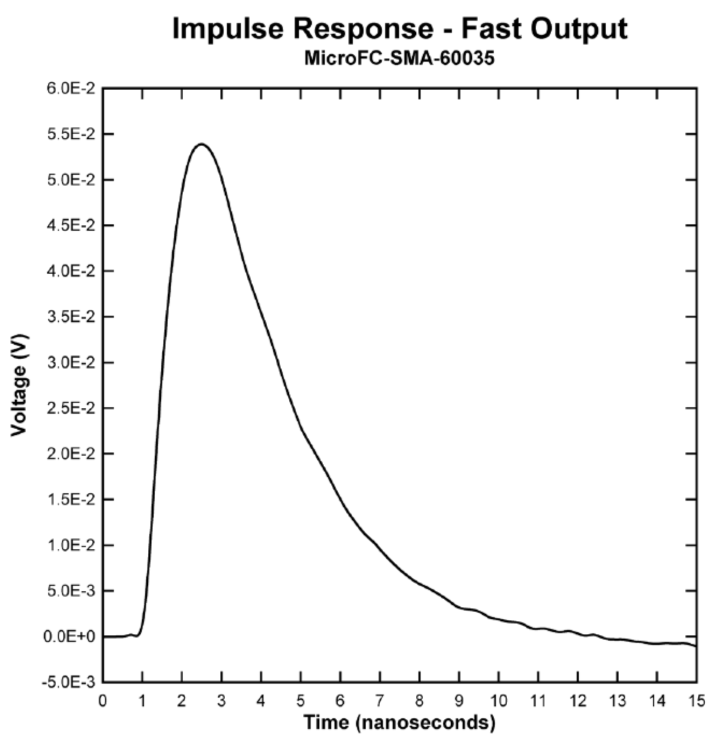
Fast SiPM Signals

SensL development

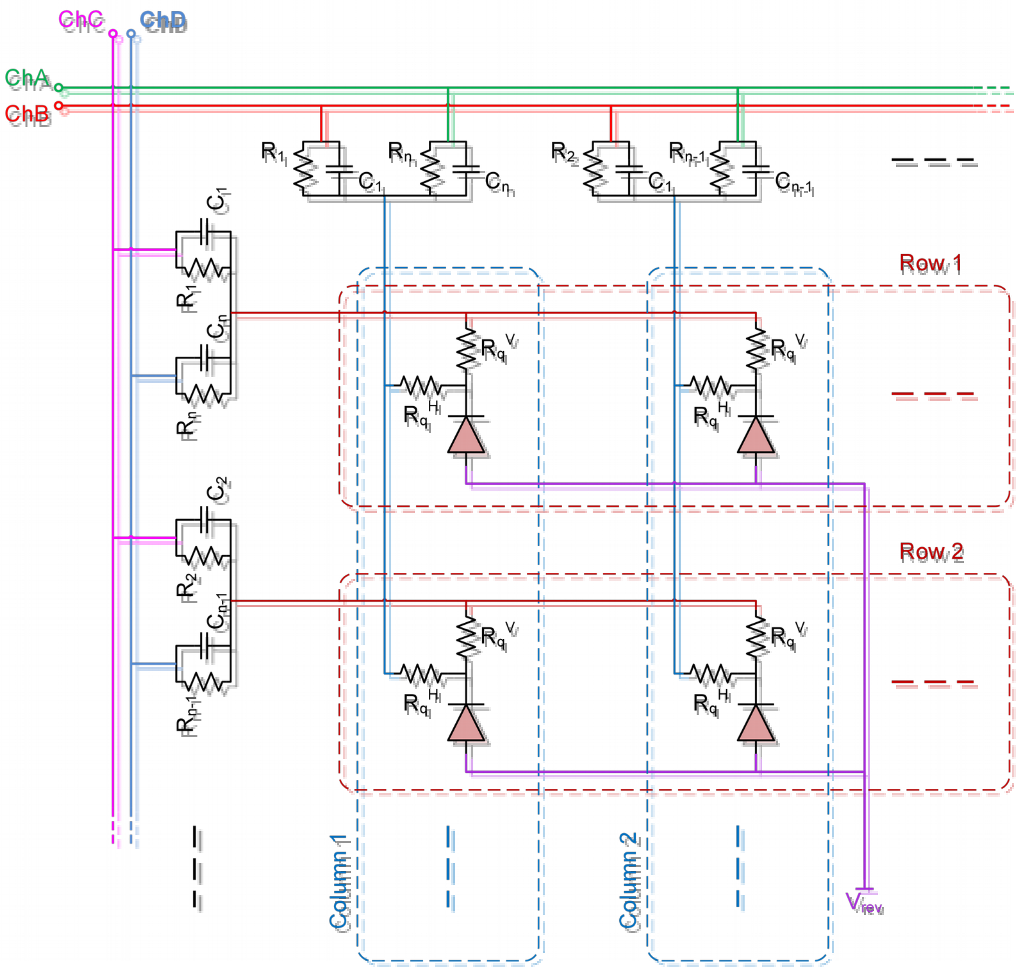
Tapping the signal between
the quench resistor and diode





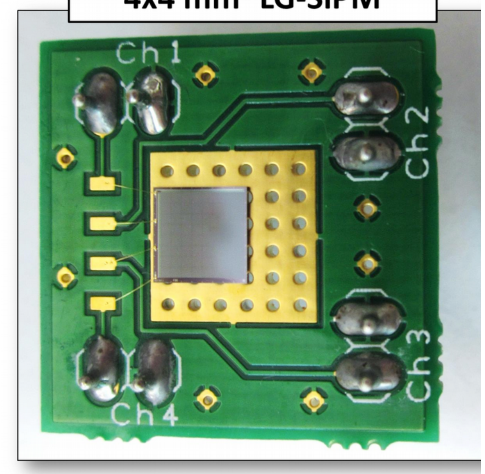


FBK: Linearly-graded SiPM (LG-SiPM)



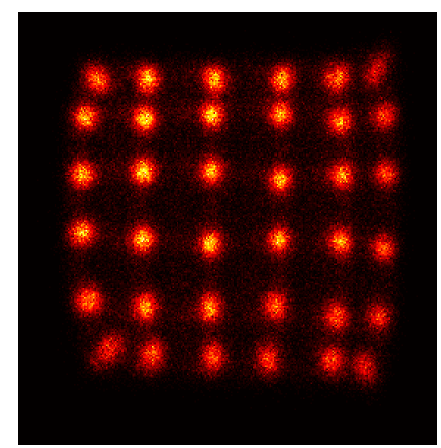
SiPM with integrated charge division readout
→ X-Y resolution

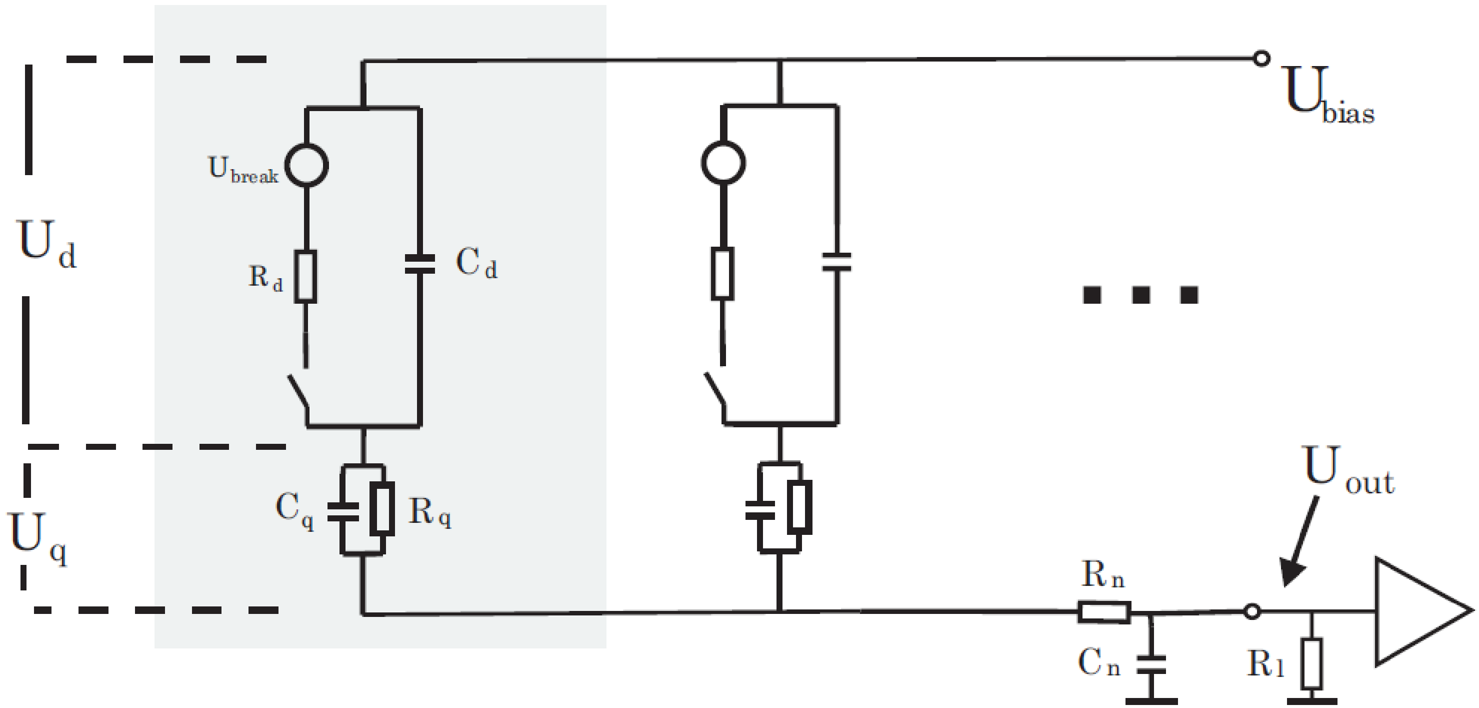
4x4 mm² LG-SiPM



Flood map

T = 25 °C

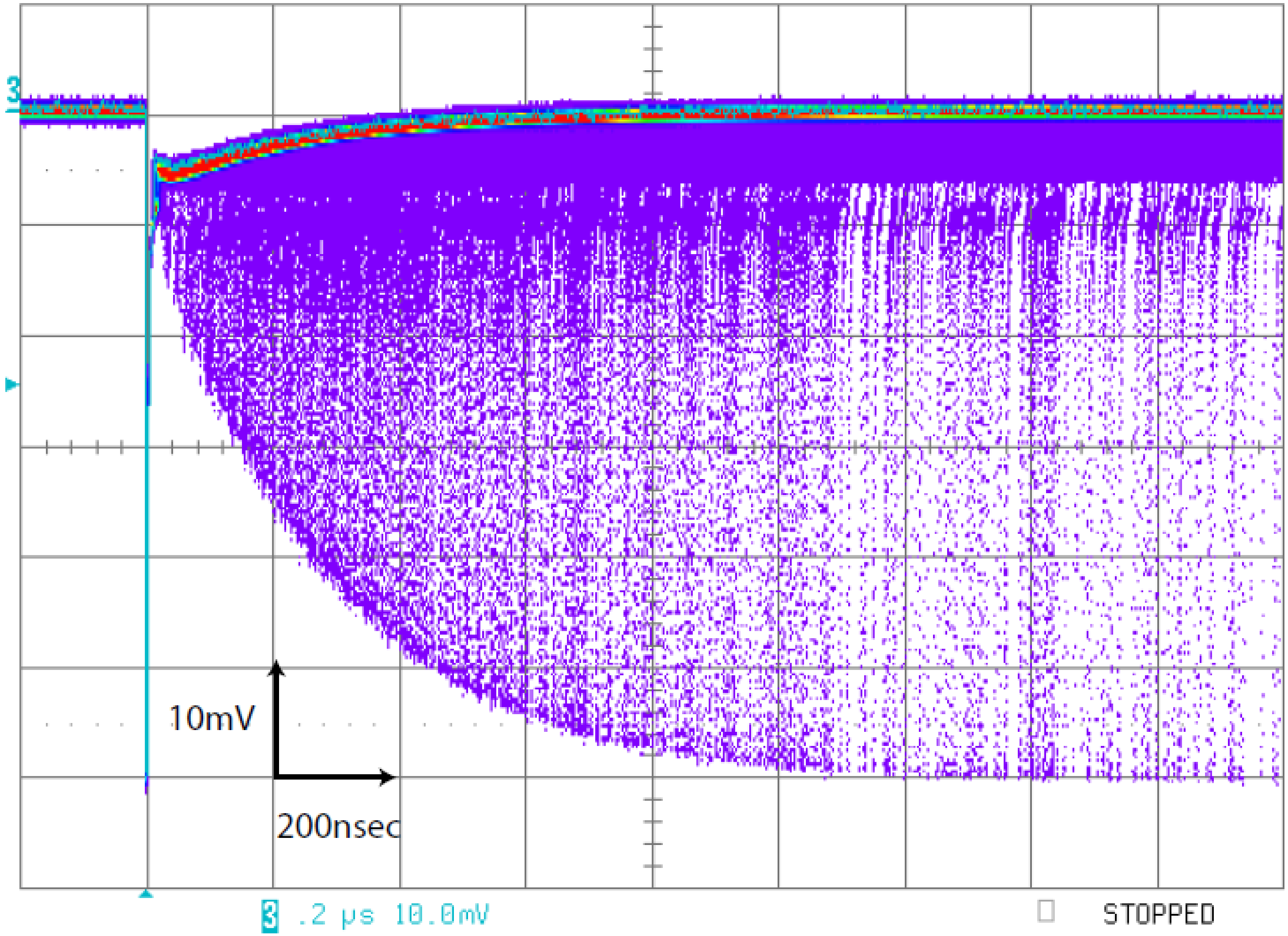




Replacement circit

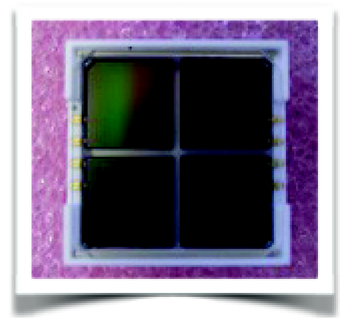
Electrical behaviour is very well understood
i.e. pulse shapes, dynamic range? See Elena's talk, cell recharge behaviour etc.
Much of which dates back to the study of single cell SPADs

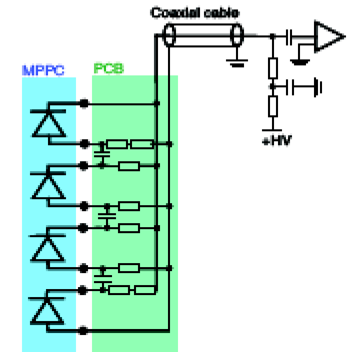
Pulse shapes from Thesis



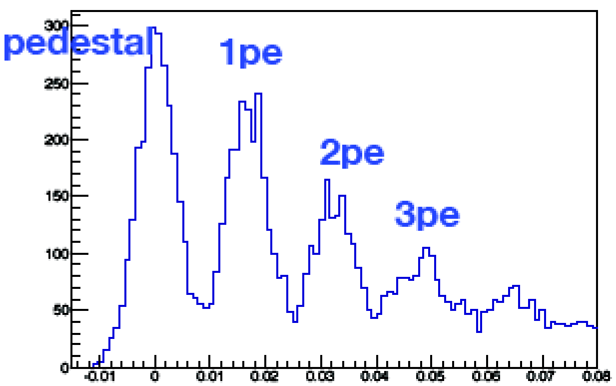
Direct Dark Matter Detection

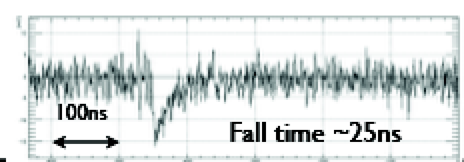
- DUV-sensitive MPPC developed for MEG II LXe detector
  - Hamamatsu MPPC S10943-4372
  - PDE≳20% at λ=175nm
  - 12×12mm² (discrete array of four 6×6mm² chip)
  - 50μm cell pitch
  - Metal quench resistor
  - Suppression of after-pulsing/cross-talk
  - Operational at LXe temp. (165K)

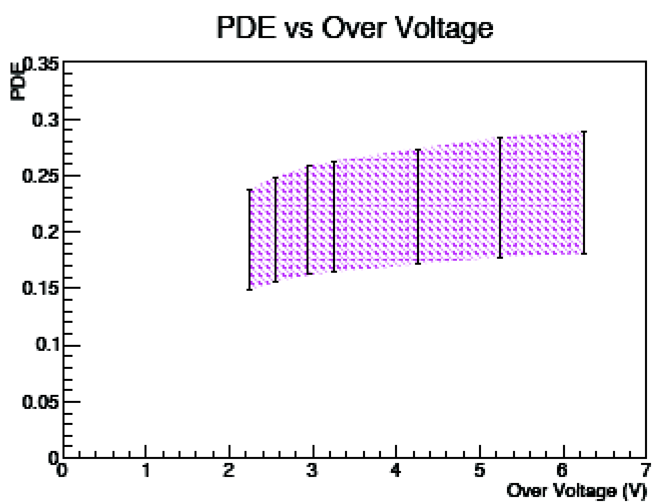




Four segment chips connected in series on readout PCB

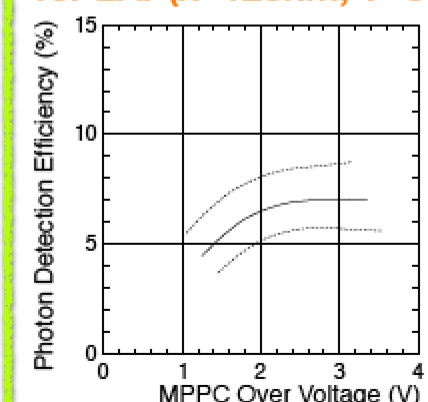






WO et al., NIMA 787(2015)220

Same technology applied for LAr (λ=128nm, T=87K)

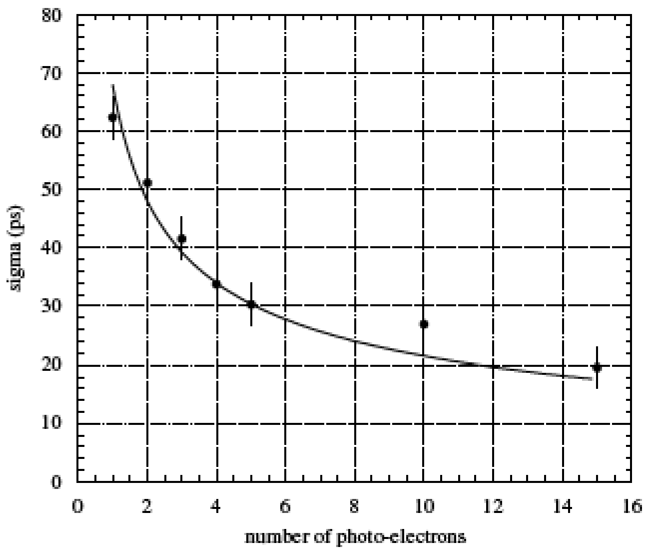


T. Igarashi et al., arXiv:1505.00091

W.Ootani,"SiPM, Status and Perspectives", Special Workshop on Photon Detection with MPGDs, June 10-11, 2015 CERN

Timing

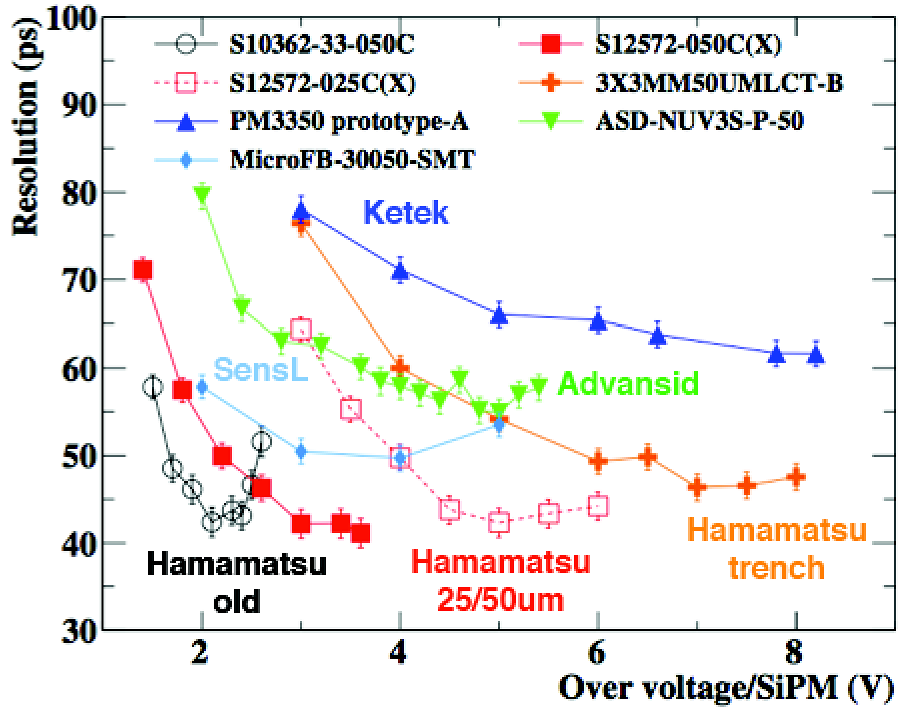
- Timing resolution for many photons



G. Collazuol et al., NIMA 581(2007)461

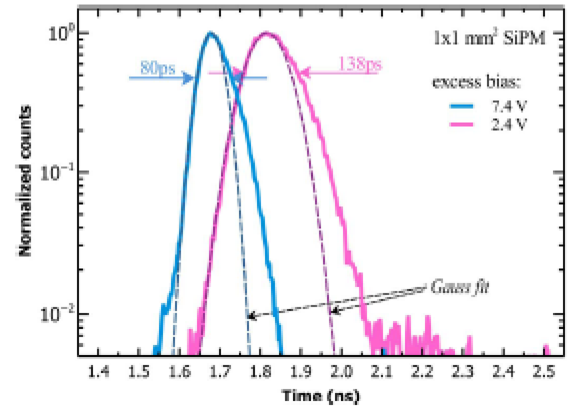
Fast plastic scintillator (BC422 60×30×5mm³)
readout by 6 SiPMs

P. W. Cataneo, WO, et al. IEEE-TNS 61(2014)2657

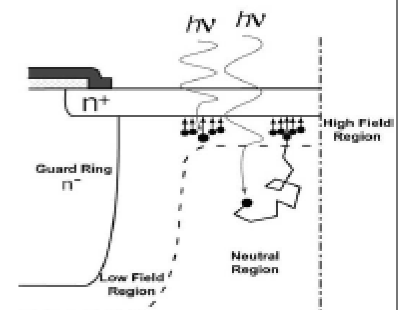


- Better resolution at higher ΔV (gain, PDE, SPTR)
- Saturated due to dark noise or after-pulsing

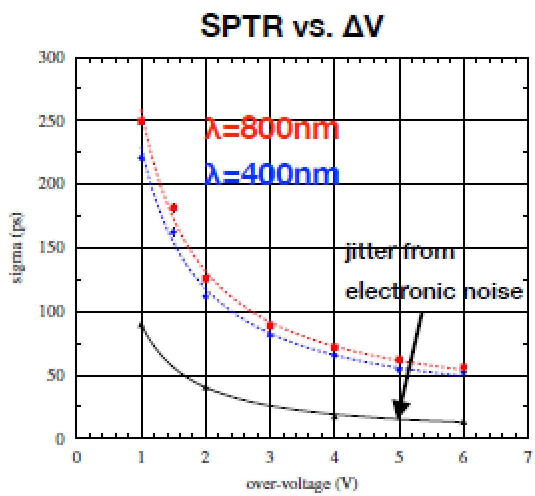
- SiPM signal charge generated in very thin layer (~a few μm)
- SiPM has an excellent Single Photon Time Resolution (SPTR).
  - Major component: Gaussian jitter ~O(100ps) (FWHM)
  - Minor slow tail (~O(ns)) from carrier drift from neutral region
- Strong dependence on ΔV, weak dependence on λ



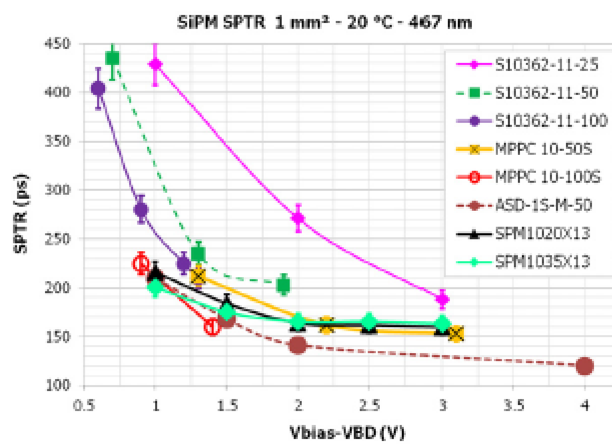
F. Acerbi et al., IEEE-TNS 61(2014)2678



S. Cova et al., NIST Workshop on Single Photon Detectors 2003

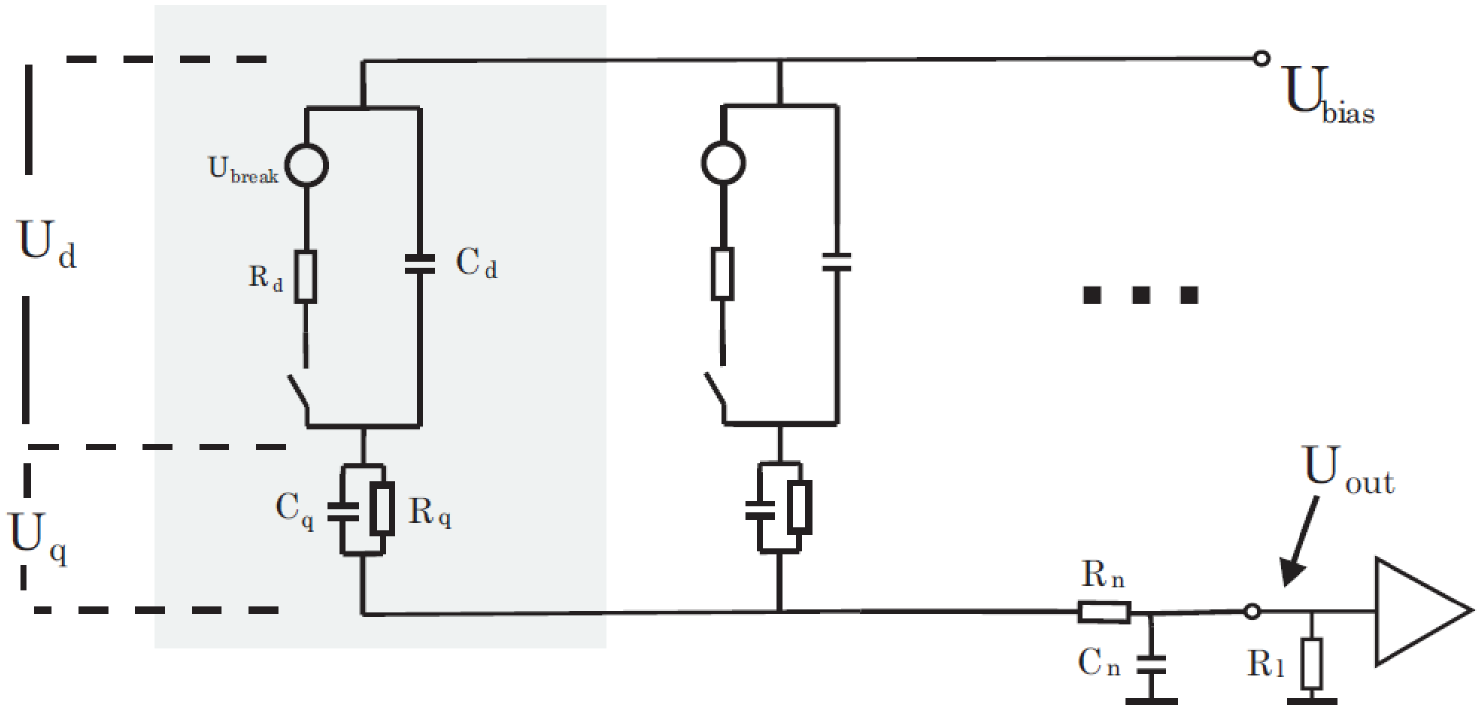


G. Collazuol et al., NIMA 581(2007)461



V. Puill et al., NIMA 695(2012)354

Small Signal Replacement Circuit



Replacement circuit

Electrical behaviour is very well understood

Much of which dates back to the study of single cell SPADs